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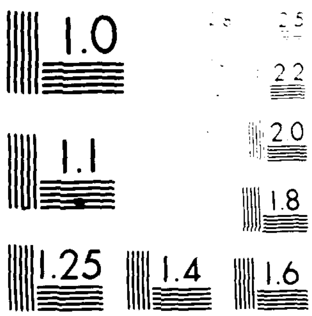
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Artificial circulation and hypolimnetic aeration have been [illegible]ccessfully in management of eutrophic reservoirs to alleviate water qual[illegible] problems, control algal blooms, and improve fish habitat. This report includes: (a) a comprehensive review of aeration/circulation techniques and past experiences encompassing literature from January, 1972, through December, 1980; (b) statistical analyses of artificial circulation experiences to examine the causes of alternative responses to treatment; (c) a summary of morphometric

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20. ABSTRACT (Continued).

and water quality data for 107 reservoirs managed by the U. S. Army Corps of Engineers; and (d) a generic evaluation procedure for alternative management applications in reservoirs.

Artificial destratification by mechanical pumping or diffused-air mixing usually elevates dissolved oxygen content of the lake by bringing anoxic bottom waters to the lake surface where aeration occurs through contact with the atmosphere. Oxygenation may cause precipitation of phosphate compounds and inhibition of nutrient release from sediments, but invasion of benthic macroinvertebrates into the profundal zone may play a role in maintenance of high phosphorus release rates from oxygenated surficial sediments. Water quality generally improves after treatment, but undersizing of water pumps or improper timing of destratification relative to occurrence of algal blooms can aggravate existing oxygen deficits.

When the mixed depth is increased, models of algal production predict a decline in the ratio of photosynthetic rate to respiration rate and a consequent decline in algal biomass per unit area of lake surface. With sufficient mixing, a drop in pH of the upper waters is observed, followed by a shift from nuisance blue-green algae to a mixed assemblage of green algal species. Zooplankton and benthic macroinvertebrates often increase during artificial circulation as a result of habitat expansion and possible enhancement of food resources. Although short-term increases in fish growth and yield have been attributed to improvement of food and habitat, long-term observations are unavailable.

Hypolimnetic aeration improves water quality without disrupting thermal stratification. Although the potential benefits of hypolimnetic treatment in controlling algal blooms are more limited than those realized with whole lake mixing, the risk of adverse impacts appears to be lower for hypolimnetic aeration. Oxygenation of downstream reaches can be achieved by hypolimnetic aeration or oxygenation, localized mixing, aeration in the outlet works, and tailwaters aeration.

Summary statistics (mean, range, and correlation coefficients) were calculated for morphometric and water quality variables measured in 107 U. S. Army Corps of Engineers' reservoirs as part of the National Eutrophication Survey by the U. S. Environmental Protection Agency.

An annotated bibliography of aeration/circulation experiences is included as an appendix to this report.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic meters per second
feet	0.3048	meters
gallons (U.S. liquid)	3.785412	cubic decimeters
horsepower (550 foot-pounds per second)	0.7456999	kilowatts
horsepower (550 foot-pounds per second) per cubic foot	26.334108	kilowatts per cubic meter
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
tons (2,000 lb, mass)	907.1847	kilograms

ENVIRONMENTAL ASPECTS OF ARTIFICIAL AERATION AND OXYGENATION OF RESERVOIRS: A REVIEW OF THEORY, TECHNIQUES, AND EXPERIENCES

PART I: INTRODUCTION

1. Impoundment of river waters has extensive impacts on water quality and the surrounding environment (Symons 1969; Baxter and Glaude 1980). Climate, nutrient loading, water retention time, and basin morphometry interact to determine physiochemical and biological conditions in reservoirs as well as in downstream reaches. With a long retention time and sufficient water depth, the stage is set for development of a true phytoplankton. High nutrient loadings combined with thermal stability during the summer months may produce nuisance algal growth and a high biological oxygen demand (BOD) throughout the water column. Production levels are ultimately related to the hypolimnetic oxygen deficit (Hutchinson 1957; Charlton 1980) and hence the potential for further deterioration of water quality through chemical transformations in surficial sediments.

2. Ambient levels of dissolved oxygen directly influence the distribution, abundance, and behavior of aquatic organisms (Hutchinson 1957; Davis 1975) and regulate nutrient release at the sediment-water interface (Mortimer 1971; Holdren and Armstrong 1980). In eutrophic reservoirs, hypolimnetic oxygen depletion may have adverse impacts on water supplies, fisheries, and downstream environments (Symons 1969; Tennessee Valley Authority (TVA) 1978). Oxygen depletion in bottom waters degrades biological habitats and restricts the distribution of fish populations. Moreover, food resource levels in benthic habitats of the profundal zone are depressed during summer stratification (Wilhm and McClintock 1978). In extreme cases, thermal instability during late summer or autumn may mix anoxic hypolimnetic waters throughout the reservoir, precipitating a massive fishkill. In water supply reservoirs, low pH combined with high levels of iron and manganese in bottom waters can produce severe corrosion problems and complaints from consumers regarding noxious tastes and odors. In 9 of the 18 reservoirs studied by TVA (1978), low concentrations of dissolved oxygen in the release had undesirable effects on tailwater communities, e.g., reduced productivity and diversity of both fish and macroinvertebrates. High concentrations of reduced compounds such as

iron, manganese, hydrogen sulfide, and ammonia could produce toxic reactions in tailwater organisms, although avoidance behavior resulting in downstream migrations could mitigate the potential impacts.

3. Artificial aeration techniques have proved beneficial in management of water quality problems associated with thermal stratification and hypolimnetic oxygen depletion in reservoirs (e.g., Toetz et al. 1972; Fast 1979a; Pastorok et al. 1980). Although these methods are purely symptomatic treatment, i.e., they modify the consequences of eutrophication rather than controlling nutrient influx from external sources, artificial aeration is potentially useful as a complement to external control technologies. Moreover, certain aeration/circulation methods have immediate and far-reaching effects on biological habitats and community structure. These techniques hold promise for benign management of algal blooms and fisheries through habitat manipulation. Nevertheless, past experiences have produced serious adverse impacts as well, e.g., enhancement of blue-green algae, turbidity problems, and even fishkills (Pastorok et al. 1980). Although some adverse effects may simply be "hidden costs" of the technique, others are almost certainly due to faulty design of aeration devices or improper applications following inadequate assessment of the biological community and its response mechanisms.

4. The purpose of this review is to summarize the results of past experiences in artificial aeration of lakes and reservoirs. In doing so, we wish to extend previous work (Pastorok et al. 1980) and accomplish three main objectives: (a) expansion of a comprehensive literature review of aeration/circulation to include more techniques and up-to-date experiences; (b) statistical analysis of artificial circulation techniques to examine the causes of various lake responses to treatment; and (c) development of a generic evaluation procedure applicable to aeration in U.S. Army Corps of Engineers (USAE) reservoirs.

5. The following chapters consider artificial circulation, hypolimnetic aeration, aeration of reservoir releases, characteristics of USAE reservoirs, evaluation of aeration techniques, and recommendations for future research. Artificial circulation includes all those techniques designed to provide aeration without maintaining

the normal thermal structure, e.g., artificial destratification, partial mixing, and whole lake mixing to prevent stratification. Hypolimnetic aeration by injection of either air or pure oxygen encompasses treatments which oxygenate bottom waters without disrupting thermal stratification.

PART II: ARTIFICIAL CIRCULATION

6. Some of the water quality problems that occur in impoundments as a result of thermal stratification can be ameliorated by maintenance of well-mixed conditions. This chapter discusses the methods available to induce lake circulation, some theoretical considerations that affect design and performance, as well as chemical and biological consequences. A review of experience gained from lake mixing is also provided.

Circulation Methods

7. Mixing devices and their applications have been reviewed in detail (Lorenzen and Fast 1977; Tolland 1977; Pastorok et al. 1980). Mixing techniques may be classified broadly as air-lift pumps, mechanical pumps, or water jet systems. In the first category, a plume of rising air bubbles upwells water, effecting turbulent mixing and direct aeration. Mechanical pumps and water jets induce circulation by plume entrainment and relative intake-discharge locations.

Air-lift systems

8. Air-lift systems involve air injection through the end of a pipe (Bernhardt 1967), through a horizontal perforated pipe (Knoppert et al. 1970; Fast 1968, 1971a, 1979b), or through special diffusers producing a column of fine bubbles (Knoppert et al. 1970; Symons et al. 1970; R.S. Kerr Research Center 1970). In a stratified lake, mixing will be induced above the air release depth in the case of an unconfined bubble plume. Enclosure of the plume within a vertical tube (e.g., Helixor) is a less common method. A variation on the confined air-lift principle is the Aero-Hydraulics Gun which uses a train of single large bubbles instead of a fine bubble plume.

9. Air compressors used in air injection systems have usually been powered by electricity, and occasionally by gasoline. Rieder (1977) has demonstrated the feasibility of wind power for driving compressors coupled to destratification systems in small prairie lakes.

10. It is important to note that although compressed air is used and the term "aeration" frequently applied, diffused-air systems

for lake mixing are not aerators but pumps. Rising bubbles induce a flow field within the impoundment that can redistribute incoming energy such that thermal stratification does not occur. As Neilson (1974) pointed out, "In general the calculations indicate that during destratification the predominant source of oxygen is the natural aeration that is enhanced by the secondary circulation set up by the rising bubbles." Smith et al. (1975) further illustrated this point by comparing the surface area of bubbles to the surface area of a "typical" lake. They concluded that the bubbles would typically constitute less than 1 percent of the lake surface area.

11. Information on relative costs of various air-lift systems is almost nonexistent. A committee of the American Water Works Association (AWWA) investigated direct capital costs and operating costs for mainly unconfined air-lift systems driven by electrically powered compressors (AWWA 1971). Both the initial cost per unit water volume and the operating cost per unit volume dropped as reservoir volume increased. Although the AWWA investigated the relationship of costs to equipment design (homemade or commercial) and operating policy (continuous, continuous in summer, intermittent in summer), no clear trends appeared. The few enclosed air pumps studied by AWWA (1971) had operating costs similar to those of unconfined plume systems, but the initial cost of the former is somewhat higher. Tolland (1977) noted that running costs of destratification devices are inexpensive relative to many other operational costs of water supply reservoirs.

Mechanical pumps

12. Mechanical destratification techniques employ diaphragm or centrifugal pumps, fan blades, or water jets to move water. Water may be pumped from the reservoir bottom to the surface (e.g., Hooper et al. 1953; Irwin et al. 1966; Ridley et al. 1966) or vice versa (e.g., Steichen et al. 1974; Garton et al. 1978; Toetz 1979a, b). A review of design and field performance of destratification techniques indicates that diffused air systems may be less expensive and easier to operate than mechanical mixing devices (Lorenzen and Fast 1977).

13. Suction pumps suspended from rafts were used to pump hypolimnetic water to the surface in King George VI Reservoir (Ridley et al. 1966), four Ohio lakes (Irwin et al. 1966), and Boltz Lake (Symons et al. 1967, 1970). Compared with diffused-air systems, these

mechanical pumps are relatively difficult to install (Symons et al. 1970) and more costly to maintain (Steel, in Tolland 1977). In terms of oxygenation capacity and destratification efficiency, diffused-air mixing techniques appear to be better than mechanical suction pumps (Symons et al. 1970; Smith et al. 1975).

14. The axial-flow pumps used at Ham's Lake and Arbuckle Lake use a large fan blade to move water from the surface downward (Quintero and Garton 1973; Garton et al. 1978; Steichen et al. 1979). Although propeller pumps located in surface waters have been successful in mixing small lakes and providing localized destratification near dam outlets, they are less effective at complete destratification of large deep lakes.

Water jets

15. The use of water jets for impoundment mixing is particularly relevant for "pump-storage" applications. Because reservoirs in the United Kingdom are frequently supplied by offstream pumping, they are particularly amenable to jet mixing. Pumped water is simply discharged at high velocity in a direction designed to induce circulation.

16. The Metropolitan Water Board of London induces mixing in their reservoirs by locating jetted-water inlets near the reservoir bottom (Ridley et al. 1966; Tolland 1977; Johnson and Davis, in press). The jet inlets are usually installed during construction of a reservoir when water quality problems are anticipated. Jetted-water systems may require a standby mixing technique for use when river inflows are insufficient.

17. Comparisons between jetted-water systems and other mixing techniques are difficult because little data on oxygenation capacity or destratification efficiency of the former exist (Tolland 1977). In most cases, jet systems would be more expensive to install than other mixing devices. For reservoirs which are supplied by pumping, however, most of the initial costs are associated with ordinary reservoir operations.

Theoretical and design considerations

Physical

18. The theoretical basis of impoundment mixing and design criteria related to physical effects are reviewed in this section.

19. Air-lift systems. The primary theoretical concerns related to the physical aspects of diffused-air mixing involve the mechanics of air supply, air distribution, and induced circulation. The relationships between air-supplied and induced mixing have been studied to some extent in laboratory experiments. Zieminski and Whittemore (1970) used a 180-gallon* plexiglass tank to study the effects of air flow rate, water body geometry, energy input, size of air bubbles, and pumping capacity of the air plume on "time of mixing." They found a "good correlation" between mixing time and power input per unit volume of water. They observed mixing times of less than 6 minutes with power input levels greater than 2×10^{-6} HP/ft^3. They also found bubble size to be relatively unimportant compared to mixing time and water flow when bubble diameters of 0.12 and 0.3 cm were compared. However, bubble diameters of 0.05 cm resulted in an approximate 20 percent increase in water flow relative to larger bubble sizes.

20. Lorenzen and Fast (1977) presented a simplified approach to determining air requirements necessary to maintain minimal temperature gradients. Based on the theory of Kobus (1968) a relationship between air release rates, depth, and the flow rate of upwelled water was established. The water flow rate as a function of height above an orifice was given by:

$$Q_w(x) = 35.6C(x + 0.8)\sqrt{\frac{-V_o \ln\left(1 - \frac{x}{h + 10.3}\right)}{u_b}} \qquad (1)$$

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* A table of factors for converting U.S. customary units of measurement to metric (SI) units is presented on page 7.

where:

$Q_w(x)$ = water flow m^3/sec

$C = 2V_o + 0.05\ m^3/sec$

x = height above orifice, m

V_o = air flow, m^3/sec at 1 atm

h = depth of orifice , m

$\mu_b = 25V_o + 0.7\ m^3/sec$

21. This relationship was used in a detailed simulation model (Chen and Orlob 1975) to compute temperature profiles over time for a variety of lake sizes and shapes with different air release rates. The original document (Lorenzen and Fast 1977) provides detailed results as well as procedures to select compressor sizes and diffuser design characteristics. As a general "rule of thumb" it was found that approximately 30 standard cubic feet per minute (SCFM) of air per $10^6\ ft^2$ of surface area ($9.2\ m^3/min \cdot 10^6\ m^2$) is required to maintain good mixing.

22. Torrest and Wen (1976) have provided a more detailed analysis as well as hydraulic model studies of air plume induced circulation. Of particular interest in the work of Torrest and Wen is the definition of a "circulation cell." Based on model studies and surface velocity measurements,it was found that circulation cells would be expected to extend a distance equal to four times the depth of air release from each side of a line source diffuser. For a point source diffuser, circulation cell radii were found to be approximately six to seven times the depth of the diffuser.

23. Davis (1980) has provided a combined theoretical and empirical approach to design of diffused-air mixing systems. The procedure is based partially on consideration of the total theoretical energy required to destratify a stratified reservoir. The theoretical energy required is estimated from an assumed density gradient plus incoming solar radiation. Stability is the difference between the total potential energy of the mixed (isothermal) system and the stratified system. This is given by:

$$S = g(\Sigma\ \rho_{im}V_ih_i - \Sigma\ \rho_{is}V_ih_i) \qquad (2)$$

where:

S = stability, J

g = acceleration due to gravity, m/sec^2

ρ_i = density of layer i, kg/m^3

V_i = volume of layer i, m^3

h_i = height of centroid of layer i, m

m = mixed

s = stratified

24. The total theoretical energy required in terms of joules (J) is:

$$E = S + R - W \tag{3}$$

where:

S = stability, J

R = heat input, J

W = wind energy, J

25. R is the heat input required to achieve stability during summer. R may be calculated using 5 J m^{-2} day^{-1} (Davis 1980). Since wind energy is intermittent and somewhat unpredictable, it is neglected in the design procedure. This ensures that the mixing device by itself will be powerful enough to circulate the reservoir in the absence of wind.

26. Based on experience, Davis notes that the energy input by a mixing device should be 20 times the theoretical energy required. The energy input (in joules) by a compressed air diffuser is given by:

$$E_d = \rho g H_o Q T \ln\left(1 + \frac{D}{H_o}\right) \tag{4}$$

where:

ρ = water density, kg/m^3

H_o = 10.4 m (1 atm)

Q = free air flow rate, m^3/sec

T = time to achieve destratification, sec

D = depth of diffuser, m

27. The required air flow is then:

$$Q = \frac{1.196E}{T \ln\left(1 + \frac{D}{10.4}\right)} \tag{5}$$

28. In order for the air bubbles to effectively induce circulation

they must be distributed so that energy is not wasted. According to Davis, a line source of air induces more flow than a series of discrete point sources. He has also noted that the volume of water entrained by the air bubbles should be 2.5 times the volume of the reservoir. Based on a paper by Bulson (1961), the volume of water entrained by a perforated pipeline source can be expressed as:

$$V_e = 0.486LT \left[\frac{gQ}{L}\right]^{1/3} \left[1 + \frac{D}{10.4}\right]^{-1/3} \ln \left[1 + \frac{D}{10.4}\right] \quad (6)$$

where:

V_e = volume of water entrained by air bubbles from line source, m^3

L = length of diffuser

29. The length of perforated pipe is thus given by:

$$L = 3.73 \left\{ \frac{V^3 \left(1 + \frac{D}{10.4}\right)}{T^3 Q \left[\ln\left(1 + \frac{D}{10.4}\right)\right]^3} \right\}^{1/2} \quad (7)$$

where:

V = reservoir volume, m^3

30. Davis provides further details and diagrams to compute pressure requirements, required anchors, and air flow rates through each perforation. He recommends 0.8-mm diameter holes for the diffuser.

31. For an example reservoir of 20 x 10^6 m^3 volume, 20-m maximum depth and 1.2 x 10^6 m^2 surface area, Davis' procedures result in a recommended 70 l/sec free air flow rate distributed through 250 m of perforated pipe. The calculations developed by Lorenzen and Fast (1977) would result in approximately 120 l/sec as the recommeded free air flow.

32. Mechanical pumps. Early efforts to destratify lakes used mechanical pumps to transport water from the hypolimnion to the epilimnion, e.g., Symons et al. (1970) used a 12-horsepower mixed-flow pump in Boltz Lake. Steichen et al. (1974) reported the use of a

large propeller pump to transfer water from the near surface of Ham's Lake, Oklahoma, to the hypolimnion. Since that time, the only significant mechanical pumping system (except for water jets which are discussed in the next section) that has been used for lake mixing is the propeller-type pump developed by Garton. This system consists of a float mounted motor with a shaft and submerged propeller or fan blade. Water is pumped downward from the epilimnion to the hypolimnion.

33. Garton and Punnett (1978) provide design criteria for the Garton pump. They recommend that velocities be sufficient for the plume to reach the lake bottom and the pump flow rate be such that the normal volume of the hypolimnion be pumped every two days.

34. McLaughlin and Givens (1978) conducted scale-model studies of Garton pumps and concluded that they can be effectively used to either destratify a lake or provide local destratification to improve quality of low level reservoir releases (also see Dortch and Wilhelms 1978).

35. Jet pumps. Jet discharges, both from recirculating pumps and from normal supply systems, have been used in a number of locations, primarily in the United Kingdom. From scale-model studies of recirculating pumps, Dortch (1979) concluded that hydraulic destratification can effectively mix an impoundment by pumping a small percentage of the total lake volume. Destratification was accomplished in a laboratory flume by pumping as little as 3 percent of the volume. Important variables were pumping rate, port velocity, density, relative volume of strata, and intake and discharge orientation. Sobey and Savage (1974) developed a mathematical model of forced circulation in a cylindrical reservoir. For this simplified geometry it was concluded that inflow momentum will induce a slow-moving, large-scale circulation which is influenced by the aspect ratio (diameter/depth) and boundary roughness. They found that, for the conditions modeled, the jet Reynolds number and the jet Froude number did not significantly influence circulation. Since this model was applied to horizontal circulation and did not consider density effects, it is therefore of limited value in analyzing destratification procedures.

36. Considerable theory and experience has been developed by the Water Research Centre in Great Britain (Tolland 1977, 1978). Jetted subsurface inlets are used in several of the pumped storage reservoirs of the Thames Water Authority. The objectives of the systems are:

a. To entrain and disperse large quantities of water from any stratified layer, thereby producing reaeration of the reservoir.

b. To circulate the whole body of water and promote general mixing.

37. The theoretical basis and design criteria are semiempirical and intended to provide guidance on jet requirements to maximize vertical mixing by entraining as much water as possible.

38. Johnson and Davis (1980) note that the energy input required should be sufficient to overcome net heat energy added to the reservoir and that the efficiency of energy transmission associated with a jet system is about 2-5 percent. In temperate climates the required energy, E_r (J/s), can be estimated by:

$$E_r = \frac{h_e A}{86400\ \eta} \tag{8}$$

where:

h_e = the approximate heat energy added by solar radiation, $5 J/m^2 \cdot day$

A = reservoir surface area, m^2

η = efficiency of energy transmission, dimensionless

39. The kinetic energy of the fluid is related to pumping rate and nozzle velocity by:

$$E_r = 1/2 \rho Q u^2 \tag{9}$$

where:

ρ = water density, kg/m^3

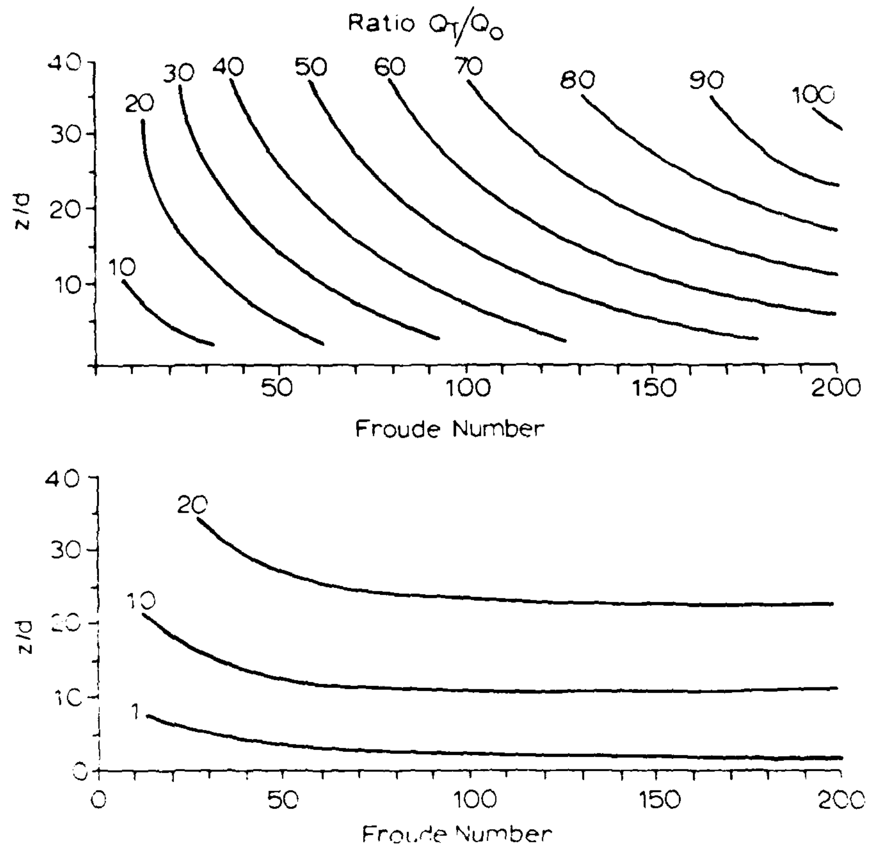
Q = inlet pumping rate, m^3/sec

u = mean exit velocity, m/sec

40. For pumped storage operations the available flow Q is dictated by other considerations,whereas for recirculating systems the value of Q is a decision variable. The design problem is to maximize the efficiency of energy transfer to prevent thermal stratification.

41. Figure 1, from Tolland (1977) illustrates the ratio of total flow to jet discharge flow for different relative depths and Froude numbers for both horizontal and inclined (22.5°) jets.

42. The choice of jet angle, discharge velocity,and in some cases flow rate will depend on reservoir configuration,density differences,and energy costs.



Key: z = Depth
d = Diameter of jet orifice
Q_T = Total discharge
Q_o = Jet orifice discharge

The upper graph shows the family of curves for the ratio Q_T/Q_o for different relative depths and Froude number for a horizontal jet. The lower graph shows this for a jet inclined at 22.5° to the horizontal. Comparison of the two graphs shows that horizontal jets entrain more, i.e. a higher Q_T/Q_o ratio.

Figure 1. Jet entrainment performance (taken from Tolland 1977).

Chemical

43. The chemical effects of circulation are discussed in the following sections dealing with dissolved oxygen concentrations, other gases, pH, chemistry of the sediment-water interface, and major nutrients.

44. Dissolved oxygen. The dissolved oxygen concentrations in lake waters result from a dynamic summation of gains (photosynthesis, atmospheric exchange) and losses (respiration, chemical oxidation, atmospheric exchange). During thermal stratification, the vertical distribution of oxygen may be closely related to depth profiles of producers and consumers. Virtually all sources and sinks of oxygen can be affected by mixing. As discussed above, artificial aeration by direct exchange across the air-bubble/water interface is probably less important than exchange with the atmosphere. Treatment effects on temperature, photosynthetic rate, respiration rate, and chemical oxidation processes will also influence oxygen balance (Toetz et al. 1972).

45. Assuming a clinograde dissolved oxygen (DO) profile during summer stratification (i.e., eutrophic lake), mixing should immediately increase the oxygen content of lower waters while decreasing surface concentrations. If isochemical conditions are achieved soon after artificial destratification, the resultant DO concentration at each depth may simply equal the weighted average concentration before circulation. In some cases, mixing of hypolimnetic waters, which are high in biological and chemical oxygen demand, throughout the lake should depress the final DO concentration below the previous weighted average. Temporary depression of DO at all depths after mixing could produce a fishkill or other undesirable effects on commercial or recreational resources.

46. Papst et al. (1980) describe the relationships among natural breakdown of thermal stability, algal blooms, and summer oxygen depletion in shallow pothole lakes of the Canadian prairie. Severe oxygen deficiencies and fishkills only occur at times when thermal instability produced by wind action and low insolation coincides with or follows a period of algal bloom collapse (also, cf. Barica 1978).

47. Both the timing of artificial mixing relative to algal blooms and the potential for oxygen consumption will determine the

success of a given aeration system. Several models may be used to predict the hypolimnetic oxygen deficit in lakes, a first step toward the prediction of oxygen concentrations (e.g., Cornett and Rigler 1979; Charlton 1980). For example, Cornett and Rigler (1979) obtained empirically a regression equation relating areal hypolimnetic oxygen deficit (AHOD, mg O_2 m^{-2} day^{-1}) to areal phosphorus retention (R_p, mg m^{-2} yr^{-1}), mean volume-weighted temperature of the hypolimnion (T_H, ^oC), and mean thickness of the hypolimnion (Z_H, m). That is,

$$\text{AHOD} = -277 + 0.5\ R_p + 5.0\ T_H^{1.74} + 150\ \ln Z_H \qquad (10)$$

For large, deep reservoirs, however, this equation may overemphasize the effect of hypolimnion size (Z_H) on AHOD (Walker 1979; Cornett and Rigler 1980).

48. A more general model is given by Charlton (1980) who relates consumption of oxygen in water (WOC) and sediment oxygen consumption (SOC) to the areal hypolimnetic oxygen deficit:

$$\text{AHOD} = \frac{\text{SOC}}{A_n t} + \frac{\left(\text{WOC}\right) Z_n}{V_n t} \qquad (11)$$

In this equation, Z_n is the mean hypolimnion thickness, A_n equals hypolimnion area, V_n equals hypolimnion volume, t is time since onset of stratification, and other terms are defined above. After deriving specific empirical models, Charlton (1980) concluded that hypolimnion oxygen consumption reflects hypolimnion thickness, temperature, and lake productivity. Although Equation 10 applies mainly to small lakes, Charlton's empirical formulations are based on data from a wide range of basins including the Great Lakes.

49. Using a time series approach, Ivakhnenko and Gulyan (1972) described the oxygen concentration in experimental ponds as a function of artificial aeration intensity and oxygen concentrations in control and experimental ponds over the previous eight hours. They derive a relationship to predict the amount of air necessary to achieve a given oxygen concentration. Although their approach is potentially useful, it is much too complex to present in detail here.

50. Long-term effects of artificial mixing on lake oxygen levels are less predictable than immediate phenomena. Unless the

mixing system is undersized, circulation should increase average oxygen content of the lake. Some decrease of oxygen levels in the surface layer may occur when high concentrations were maintained before circulation by surface algal blooms. Mixing of phytoplankton throughout the lake will prevent surface accumulations and lower total primary production (see below "Phytoplankton: production, concentration, and biomass"). Some reduction in average DO concentration should eventually result whenever circulation continues throughout the summer, although percent oxygen saturation may remain high. Because mixing increases average water temperature, the solubility of oxygen in water is decreased.

51. Aeration over a long period may reduce sediment oxygen demand since lowered primary production results in less organic inputs to the lake bottom. The realization of benefits from lower oxygen consumption by sediments might take several years, however. The oxygen consumption rate does not correspond to short-term (e.g., yearly) changes in amount of sedimented organic matter; rather, it appears to reflect a long-term integral of organic sediment inputs (Graneli 1978; Mathias and Barica 1980).

52. Mathias and Barica (1980) discuss the factors which control oxygen depletion in ice-covered lakes. Oxygen depletion rate was inversely related to mean depth and directly related to the ratio of sediment area to lake volume. Although respiration per unit water volume varied little among lakes, the respiration rate associated with the sediments of eutrophic lakes was about three times higher than that of oligotrophic lakes.

53. Other dissolved gases. During thermal stratification in a eutrophic lake, carbon dioxide, hydrogen sulfide, and ammonium will ordinarily accumulate in the hypolimnion (Hutchinson 1957). Artificial destratification brings hypolimnetic waters to the lake surface where excess gases may be released to the atmosphere. Nitrification of NH_4^+ to NO_3^- will also be an important mechanism for elimination of reduced nitrogen compounds (Brezonik et al. 1969). In general, the concentration of gases in surface waters should increase, whereas concentrations at lower depths should decrease following destratification. If an adequate mix is achieved, gas distributions will become isochemical with depth.

54. Although extremely high concentrations of dissolved oxygen (more than twice the air-saturation level) fail to harm freshwater fish through direct toxicity, combined pressures of oxygen and nitrogen gas in excess of hydrostatic pressure may induce "gas bubble disease" (Shumway and Palensky 1975; Weitkamp and Katz 1980). Some concern has been expressed that diffused-air systems used to destratify lakes might cause supersaturation of nitrogen gas relative to surface hydrostatic pressures (e.g., Fast 1979a, b). Dissolved nitrogen concentrations of only 115 to 120 percent saturation can cause substantial mortality among salmonids (Rucker 1972; Blahm et al. 1976).

55. During spring circulation, N_2 levels equilibrate at 100 percent saturation with respect to surface temperature and pressure. Warming of the metalimnion and hypolimnion during summer results in N_2 supersaturation relative to surface pressure and ambient temperature at depth. Nevertheless, hydrostatic pressure probably maintains this "excess gas" (relative to surface pressures) in solution. The entire water column is usually close to 100 percent saturation with respect to depth-specific temperatures and pressures (Hutchinson 1957).

56. Little information is available for predicting the effects of artificial mixing on N_2 concentrations. Absolute concentrations of N_2 will increase with depth in stratified lakes, and lower waters will be saturated with respect to surface temperature and pressure. Thus, it seems likely that mixing would vent some N_2 to the atmosphere, as is the case with other gases discussed above. Initial effects of mixing high N_2 water into the surface layer have not been investigated. To what extent aeration causes N_2 supersaturation with respect to depth-specific conditions is unknown.

57. pH. In many lakes, pH is controlled by the bicarbonate system (Hutchinson 1957; Wetzel 1975). Based on predicted changes in CO_2 concentrations, artificial destratification should cause a decrease in pH of surface waters and an increase in pH near the lake bottom. Intense mixing should lead to isochemical conditions of pH with depth. Control of algal blooms near the surface will prevent high biogenic pH. Because changes in CO_2 and related pH effects have a critical role in controlling phytoplankton species composition, these topics are be considered further in a later section.

58. Nutrients: phosphorus, nitrogen. Artificial mixing before the onset of stratification should prevent the accumulation of nutrients in bottom waters during summer. Under thermally stable conditions, phosphate and ammonium would normally reach high levels in the hypolimnion of a eutrophic lake due to release from anaerobic sediments (e.g., Mortimer 1941, 1942; Fillos and Swanson 1975; Freedman and Canale 1977; see below, "Redox reactions and internal nutrient loading"). Relative to the hypolimnion, the epilimnion is deficient in available nutrients as a result of phytoplankton uptake, sedimentation, and outflow losses. Artificial destratification after a sufficient stagnation period will therefore mix nutrient-rich bottom waters into the surface layer, increasing phosphorus and nitrogen concentrations there. Some loss of total $PO_4^{\equiv}$ and NH_4^+ from the water column is expected also. Oxygenation of previously anoxic waters containing soluble iron and manganese leads to precipitation of phosphate through formation of Fe^{+++} and Mn^{+++} complexes (Mortimer 1941, 1942; Hutchinson 1957; Fitzgerald 1970). Reduced nitrogen compounds will decrease in concentration as NH_3 is vented to the atmosphere and as nitrification proceeds. Accordingly, NO_3^- concentrations are higher throughout the lake after destratification than before. Increased concentrations of nutrients in the upper waters should be a temporary phenomenon as rapid uptake by phytoplankton will deplete $PO_4^{\equiv}$ and NO_3^-.

59. Average concentrations of total phosphorus and total nitrogen in the water column may be elevated by artificial mixing. Induced turbulence maintains organic particles in suspension; moreover, artificial circulation will resuspend bottom deposits at high pumping rates. The availability of particulate phosphorus and nitrogen to phytoplankton is variable according to species and environmental conditions. In any event, transformation of resuspended organic matter to available forms is possible, but the complexity of biotic-abiotic interactions precludes further predictions without mass balance modeling of specific lakes and mixing systems.

60. Redox reactions and internal nutrient loading. Under anoxic conditions in bottom waters, a low redox potential will allow large releases of phosphates from decomposing sediments due to dissolution of ferrous phosphate and other iron complexes (e.g., Mortimer 1941, 1942; Fillos and Swanson 1975; Chen et al. 1979). The

rate of phosphorus release into anoxic hypolimnetic waters has been successfully modeled as a diffusion process (Kamp-Nielsen 1974; Freedman and Canale 1977; Holdren et al. 1977).

61. When overlying waters are oxygenated, phosphates still move from deeper anaerobic layers of the sediments toward the surface; but once the phosphates near the top few millimeters of sediment, known as the oxidized microzone, they are largely retained as ferric complexes and prevented from entering the water (Mortimer 1941, 1942; Hutchinson 1957; Fillos and Swanson 1975). Thus, "conventional wisdom" presumes that artificial mixing will reduce internal loading of nutrients by maintaining the oxidized microzone (Toetz et al. 1972; Dunst et al. 1974; Fast 1979a). As these authors point out, this is not necessarily the case (see below). Others have postulated that ferric complexes play a minor role in controlling phosphorus regeneration (Lee et al. 1977).

62. Additional factors influencing phosphorus release from sediments may obscure the relation between DO levels and release rates (Holdren and Armstrong 1980). Water movement over the sediments generally elevates nutrient release rates, but sediment resuspension reduces dissolved reactive P levels (Holdren and Armstrong 1980). Higher temperatures stimulate bacterial activity, causing greater mineralization of organic matter and possibly oxygen depletion (Kamp-Nielsen 1975; Holdren and Armstrong 1980). Under aerobic conditions, iron-rich sediments contribute less phosphorus to overlying water than do calcareous deposits (Holdren and Armstrong 1980). Frevert (1980) concluded that little or no oxic P-release from profundal sediments of Lake Constance occurs since the iron to phosphorus atomic ratio in the oxidized surficial layer is greater than 3 - 4 (pH = 7.5 - 8.0).

63. Benthic macroinvertebrates have a major influence on nutrient release rates from sediments. When tubificid worms and emerging chironomids were abundant, Holdren and Armstrong (1980) found high P release, independent of water mixing and oxygen concentration over a wide range of conditions. Although chironomid larvae do facilitate phosphorus transfer from mud to water, possibly in a density-dependent manner (Porcella et al. 1970; Gallepp et al. 1978), tubificids are probably unimportant in this regard (Davis et al. 1975; Gallepp et al. 1978; Gallepp 1979). Others have suggested that

benthic fauna reduce nutrient exchange by decreasing diffusion gradients between sediments and water (Schindler 1975) or by modifying sediment composition (Frevert 1980). These latter effects undoubtedly depend on species-specific activities and site-specific conditions.

64. Aerobic sediments may therefore exhibit high rates of phosphorus release (Porcella et al. 1970; Holdren and Armstrong 1980). They might still act as a net sink for phosphorus depending on the balance between sedimentation and net nutrient exchange across the sediment boundary (Mortimer 1971; Graetz et al. 1973). However, observations of reduced nutrient release after water overlying the sediments is oxygenated (e.g., Frevert 1980; Holdren and Armstrong 1980) may depend on the absence of significant macroinvertebrate populations.

65. Since artificial circulation allows invasion of the profoundal zone by macroinvertebrates, high nutrient release rates may prevail even after establishment of an oxidized sediment microzone. Moreover, higher temperatures in bottom waters and turbulence induced by mixing should enhance nutrient release (Fast 1971a, 1979a). Circulation may have little effect on internal loading from sources other than profoundal sediments; e.g., nutrient leakage from macrophytes (DeMarte and Hartman 1974; Lehman and Sandgren 1978) and decomposition of littoral sediments (Wetzel 1975). The importance of internal loading in lakes with a long history of cultural eutrophication has been demonstrated (e.g., Bengtsson 1975; Freedman and Canale 1977; Larsen et al. 1975; Cooke et al. 1977), but its role in noneutrophic lakes is less clear (e.g., Schindler and Fee 1974).

Biological

66. The biological changes induced by artificial circulation are both direct and indirect. They depend on manipulations of the chemical and physical environment as well as immediate modification of organism survival and distribution. The predicted biological effects of whole lake mixing are generally related to phytoplankton concentration and biomass, phytoplankton species composition, and fisheries resources.

Phytoplankton: production, concentration, and biomass

67. The phytoplankton concentration or biomass found in the water column at a given time is dependent on growth and loss processes. Some of the main factors affecting phytoplankton growth

and removal rates are temperature, light intensity and quality, nutrient concentrations, sinking rate, grazing intensity, and disease occurrence. Although most of these parameters have received considerable attention from phytoplankton ecologists, little work has been done on formulation of models relating artificial mixing to changes in factors controlling algal loss rates. Prediction of peak biomass has concentrated on nutrient and light effects in relation to mixed depth (e.g., Murphy 1962, Lorenzen and Mitchell 1975), although a general loss rate term is sometimes incorporated (e.g., Forsberg and Shapiro 1980a). Examples of these models will be reviewed in detail below.

68. Temperature. Ambient temperature levels affect phytoplankton growth rate kinetics, photosynthetic rates, respiration rates, and nutrient uptake rates (Goldman 1980). Recent reviews of the influence of temperature on phytoplankton growth processes have emphasized the difficulties encountered in studying temperature effects in natural waters and the meager amount of field data available (Eppley 1972; Goldman 1980). Eppley (1972) suggested that temperature has little effect on phytoplankton production in the sea, probably because growth rates in nature are typically well below the potential or maximum rates. From laboratory experiments, however, it is well known that temperature can greatly influence cell physiology and growth rates. Increase of nutrient uptake rates and cell size at low temperature may compensate for lower cell division rates (Goldman 1980).

69. Temperature effects have been incorporated into models relating mixed depth to algal biomass or concentration in a general way only (e.g., see below). Although such models include terms for algal photosynthetic rates and respiration rates, specific formulation for temperature dependence are rarely given for these processes. Stefan et al. (1976) related potential growth rate to temperature by a simple equation expressing linear dependence.

70. Computation of water column temperature is usually based on a model of the reservoir heat budget. Heat exchange at the lake surface is related to solar radiation, atmospheric radiation, water surface radiation, evaporation heat flux and sensible heat flux. Specific models of these processes are available in a review by Orlob (1977).

71. As previously discussed, artificial circulation during the productive season (spring-autumn) generally leads to a decrease in the temperature of surface waters, an increase in the temperature of bottom waters, and a rise in overall heat content of the lake. Temperature-mediated effects on phytoplankton depend on the vertical distributions of species before and after artificial mixing as well as the changes in the balance between photosynthesis and respiration.

72. At present, no specific formulations have been proposed to examine temperature-related effects of artificial circulation on algal physiology. In most circumstances, the processes are complex and therefore unpredictable from simple considerations. Nevertheless, several points are worth noting. First, populations that were formerly epilimnetic will experience a slight decrease in temperature after mixing treatment. Temperature-related variation in rate of respiration may be more important in determining net algal production than are changes in gross photosynthetic rate (Lorenzen et al. 1980). If this is true, then mixing would induce a thermal-mediated drop in net production, unless surface light inhibition was important previously. In many species of algae, the light intensity that produces saturation of photosynthetic rate is positively related to temperature (Aruga 1965). Phytoplankton occupying the lower metalimnion or hypolimion before treatment will experience a rise in ambient temperature and probably a boost in net production. Since temperature relationships are species-specific (Aruga 1965), shifts in algal species composition induced by mixing will modify temperature responses. In any case, the changes resulting directly from temperature shifts related to mixing will probably be small compared with the consequences of shifts in light availability, nutrient concentrations, and other factors discussed below.

73. Light. Light intensity has a critical role in controlling algal photosynthetic rate. Phytoplankton photosynthetic rate is positively related to light intensity but cells have an upper limit (saturation level) to photosynthesis at higher light levels. Inhibition of photosynthesis may occur at extreme light intensities, especially at higher temperatures (Aruga 1965). Zison et al. (1978) have reviewed a number of mathematical formulae used to describe algal growth rate as a function of light intensity. Several different formulations have been used by researchers interested in predicting

the effects of artificial mixing on lake phytoplankton (e.g., Lorenzen and Mitchell 1973, 1975; Oskam 1978; Forsberg and Shapiro 1980a). All of these are based on calculation of integral net photosynthesis from a consideration of depth-specific photosynthetic rates, daily integral respiration, and light intensities.

74. Prediction of light intensity as a function of water depth must account for the attenuation of light by the water itself, by dissolved substances, and by suspended particulates including phytoplankton. The commonly used equation assumes exponential decay in light intensity with depth. The total attenuation coefficient is partitioned into an algal fraction (βC) and a nonalgal fraction (α) in the expression:

$$I_d = I_o \exp[-(\alpha + \beta C)d] \qquad (12)$$

where:

I_d = illumination at depth d, lux

I_o = surface illumination, lux

d = depth, m

α = attenuation coefficient for water, dissolved substances and nonalgal particles, m^{-1}

β = incremental attenuation coefficient for algae, m^2 mg Chl^{-1}

C = algal concentration, mg Chl/m^3

Note that the relative importance of each term will depend on site-specific conditions. For example, different values of algal and nonalgal attenuation coefficients are given by Talling (1971), Steel (1972), Bindloss (1976), and Jewson and Taylor (1978). Atlas and Bannister (1980) found that the extinction coefficient associated with suspended algae (β) varies with depth, water color, and algal species. The coefficient increases with depth in blue water, decreases with depth in green water and changes relatively little in blue-green water. The greatest changes between water colors were observed for green algae.

75. Haffner and Evans (1974) discussed the relationship between suspended particles and light penetration in reservoirs of the Thames Valley, U.K. They found that light attenuation was highly correlated with total particulate surface area, but less so with total

particulate volume. They suggested that artificial mixing aided the suspension of high silt loads in Queen Elizabeth II and Wraysbury Reservoirs, limiting the depth of light penetration.

76. Jewson and Taylor (1978) examined the relative influence of phytoplankton and nonalgal turbidity on net planktonic photosynthesis in Irish lakes. Self-shading by phytoplankton was generally unimportant in these lakes, although it does play a role in Loch Leven, Scotland (Bindloss 1976) and Ethiopian soda lakes (Talling et al. 1973). The nonalgal component of turbidity may be high enough to severely depress photosynthetic rate per unit area of lake surface (e.g., see Jewson and Taylor (1978) for references).

77. The average light intensity experienced by an assemblage of phytoplankton in a mixed layer of depth z_m is given by Tilzer and Goldman (1978) as:

$$\bar{I}'(z_m) = \frac{1}{z_m} \int_{z=0}^{z=z_m} I'_z dz = \frac{1}{z_m} \int_{z=0}^{z=z_m} I'_o \quad e^{-\varepsilon z} dz \qquad (13)$$

where:

$I'(z_m)$ = average light intensity of exposure in mixed depth z_m, lux

I'_z = subsurface photosynthetically available radiation (PhAR) at depth z, assumed to be 0.46 of total visible light (Talling 1971), lux

I'_o = photosynthetically available radiation immediately below the surface, lux

ε = vertical light extinction coefficient, m^{-1}

Lorenzen and Mitchell (1973, 1975), Steel (1972), and others have followed Vollenweider's (1965) suggestion for use of the "standard light day" which uses a cosine function to describe the light intensity as a function of time when the number of hours of daylight and noon intensity are known.

78. The following section describes several models which have been used recently to describe the relationship between light intensity and algal photosynthesis or growth. These formulations have been chosen because each is part of a model linking mixed depth to peak algal biomass, a relationship which has been used to evaluate the effects of artificial mixing on phytoplankton. Other theoretical explorations of the relation between daily integral photosynthesis and

light attenuation include equations by Steele (1962), Vollenweider (1965), Fee (1969), Bannister (1974a, b; 1979), and Megard et al. (1979). These will not be reviewed here.

79. In evaluating the theoretical effects of artificial mixing on phytoplankton, Lorenzen and Mitchell (1973, 1975) have modeled the growth rate of algae in relation to light intensity by:

$$K = \frac{K_{max} AI}{\left[1 + (AI)^2\right]^{1/2}} \tag{14}$$

where:

K = specific algal growth rate, day^{-1}

K_{max} = specific algal growth rate at light saturation and temperature of interest, day^{-1}

A = a constant proportional to rate at low light intensities, lux^{-1}

I = light intensity, lux

80. Combining this equation with the model of light attenuation (Equation 12) and subtracting a general respiration loss term, Lorenzen and Mitchell (1973, 1975) integrated net production over the mixed depth and over Vollenweider's (1965) "standard light day" to obtain an expression for the daily rate of net production in the water column:

$$\frac{\Delta(CZ)}{\Delta T} = \frac{CK_{max}}{\alpha + \beta C}\left(\frac{1}{\Delta T}\int_0^{\Delta T} \ln(AI_o(t) + \left\{1 + [AI_o(t)]^2\right\}^{1/2}\right)dt - \frac{1}{\Delta T}\int_0^{\Delta T}\left\{\ln\ AI_o(t)\exp[-(\alpha + \beta C)Z] + (1 + \left\{AI_o(t)\exp[-(\alpha + \beta C)Z]\right\}^2)^{1/2}\right\}dt - \frac{1}{\Delta T}\int_0^{\Delta T} RCZ(dt)\Bigg) \tag{15}$$

where:

T = the time interval chosen for evaluation, hours

$I_o(t)$ = surface light intensity at time t, lux

R = specific algal respiration rate, day^{-1}

and other terms were defined previously.

81. Using a similar approach, Oskam (1973, 1978) has related gross photosynthesis per unit of lake surface and time (ΣP_{gross}) to light availability by:

$$\Sigma P_{gross} = C \cdot \frac{P_{max}}{\varepsilon_w + C \cdot \varepsilon_c} \cdot F(i) \cdot \lambda g C m^{-2} d^{-1} \qquad (16)$$

where:

P_{max} = maximum photosynthesis rate per unit of algal biomass (g C mg Chl^{-1} h^{-1})

ε_w = extinction coefficient of the water without algae (m^{-1})

ε_c = specific extinction coefficient per unit of algal concentration (m^2 mg Chl^{-1})

$F(i)$ = dimensionless function of light intensity

λ = daylight hours

82. In assessing the effects of changes in mixed depth on lake phytoplankton, Forsberg and Shapiro (1980a, b) have used a formulation developed by Megard et al. (1979) to calculate daily integral rate of phytosynthesis, π (mg C m^{-2} day^{-1}):

$$\pi = \frac{\ln(I_o/I_{z'})P_{max}c}{\varepsilon_c c + \varepsilon_w} \qquad (17)$$

where:

I_o = the intensity of PhAR just below the surface, lux

$I_{z'}$ = the intensity of PhAR at the depth z', lux

z' = a depth in the water column defined empirically as $z' = \pi/(P_{max}c)$, (meters)

c = the concentration of chlorophyll a in the mixed

layer (mg Chl m^{-3})

ε_c = the partial coefficient for the attenuation of PhAR by chlorophyll a (m^2 mg Chl^{-1})

ε_w = the partial coefficient for the attenuation of PhAR by water and substances other than chlorophyll a dissolved or suspended in the water (m^{-1})

83. This approach assumes that photosynthetically available radiation (PhAR) reaches saturation levels in the lake and that phytoplankton are uniformly distributed throughout the mixed layer (Forsberg and Shapiro 1980a).

84. Stefan et al. (1976) used the following model to describe light limitation of algal growth in Halsted's Bay, Lake Minnetonka:

$$\frac{dC}{dt} = C\left(r_1 F - r_2 - \Gamma \frac{dV}{dt}\frac{1}{V}\right) \tag{18}$$

where:

C = phytoplankton concentration, mg Chl/m^3

r_1 = growth coefficient = K_1 T , day

K_1 = temperature growth coefficient, day^{-1}

T = temperature

r_2 = loss rate = K_2 T , day^{-1}

K_2 = temperature respiration coefficient, day^{-1}

F = function relating growth to light intensity, dimensionless

V = volume of the mixed layer, m^3

Γ = constant (either 0 or 1)

The last term within the parenthesis accounts for dilution of total algal biomass (C·V) when the volume of the mixed layer is increased by dV. If the volume of the mixed layer decreases, however, there is a loss in phytoplankton mass without a change in concentration. If $dV > 0$, then $\Gamma = 1$ and if $dV < 0$, then $\Gamma = 0$. Settling losses are implicit in this model.

85. To relate algal growth to light intensity, Stefan et al. (1976) used an equation by Steele which gives linear dependence of growth rate at low light intensities, maximum growth rate at light saturation, and declining growth at excess light levels. That is:

$$F(I) = \frac{I}{I_s} \exp\left(1 - \frac{I}{I_s}\right) \qquad (19)$$

where:

$F(I)$ = light limitation coefficient, dimensionless

I = ambient average light intensity experienced by phytoplankton, lux

I_s = saturation light intensity, lux

Stefan et al. (1976) give an equation used to calculate I depending on mixed depth and light attenuation. They apply Equations 18 and 19 to different vertical strata of the lake during successive time intervals. By integrating over depth Stefan et al. (1976) simulate changes in areal algal biomass throughout the productive season (May-October) as a function of mixed depth (see below, "Peak biomass vs. mixed depth").

86. Nutrients. The formulations discussed above treat the rate of phytoplankton growth under light-limited conditions only; nutrients are assumed to be present at saturation levels. The role of nutrients in controlling algal growth is well known however. Thus, a general model must include nutrient limitation terms as well as components relating to light intensity. In the development of theories for evaluating the effects of artificial circulation, two basic approaches to modeling of nutrient limitation have been taken.

87. The first approach is exemplified by Lorenzen and Mitchell's (1973, 1975) calculation of total nutrient-limited biomass (peak algal biomass). They view nutrients as biomass limiting factors where an impoundment has a capacity to produce a certain algal biomass, X, before nutrient depletion limits further growth. The peak algal biomass supported by water column nutrients is:

$$C\bar{Z} = X\bar{Z} \qquad (20)$$

where:

C = algal concentration, mg/l

Z = depth of uniform algal distribution, m

X = capacity of system to produce algal biomass before nutrient(s) is (are) depleted, mg/l

This equation applies to well-stratified reservoirs with uniform algal distributions in the mixed layer or artificially mixed reservoirs in which uniform distributions of phytoplankton are maintained throughout the water column.

88. The second approach to nutrient-phytoplankton modeling, followed by Forsberg and Shapiro (1980a, b), views nutrients as rate-limiting factors; i.e., limiting photosynthetic rate or growth rate. (Biomass limitation is then treated by setting rate equations equal to zero and solving for a steady-state peak algal level.) The basis of this approach is an expression relating specific photosynthetic rate to cell nutrient quota (Senft 1978; Forsberg and Shapiro 1980a):

$$P_{opt} = P^{s}_{opt} \left(1 - \frac{k_q}{Q}\right) \tag{21}$$

where:

P_{opt} = the maximum specific rate of photosynthesis in saturating light (mgC $mgChl^{-1}$ hr^{-1})

P^{s}_{opt} = the maximum specific rate of photosynthesis when both nutrients and light are saturating (mgC $mgChl^{-1}$ hr^{-1})

Q = the cell quota of limiting nutrient (mg $mgChl^{-1}$)

k_q = the minimum cell quota of nutrient required for photosynthesis to occur (mg $mgChl^{-1}$)

This equation is an extension of the cell nutrient quota model developed by Droop (1973). In an attempt to incorporate external nutrient concentrations into cell quota models, a number of so-called "internal pool models" have been developed. In practice, the cell quota in Equation 21 can be approximated by the ratio of the total concentration of limiting nutrient, S_o (mg/m^3), to the concentration of chlorophyll, C, such that P_{opt} is expressed as a direct function of

total nutrient concentration (Forsberg 1980). In addition, Forsberg (1980) replaced k_q by the minimum ratio of S_o/C required for photosynthesis to occur (i.e., k_q'). Then, the maximum specific daily rate of photosynthesis (P_{max}) is described by an expression analogous to Equation 22:

$$P_{max} = P^S_{max} \left(1 - \frac{k_q'}{S_o/C}\right) \qquad (22)$$

where:

P_{max} = the maximum specific daily rate of photosynthesis when nutrients are saturating

89. More complicated "simulation" models proposed to describe algal growth under nutrient limitation (Lorenzen et al. 1980) have not been used to evaluate artificial mixing. Moreover, these models generally contain numerous parameters which are difficult or impossible to evaluate in the field.

90. <u>Loss rates: sinking, grazing, and parasitism.</u> Most modelers of phytoplankton response to destratification focus on the relation of peak algal biomass to mixed depth. Implicit in their approach is the assumption that peak biomass is not significantly altered by population losses due to extrinsic factors such as grazing, sinking, and parasitism. Of the models described above, the only one which includes extrinsic losses is the expression derived by Forsberg and Shapiro (1980a, b). These authors incorporate all losses into a single constant without specifying functional dependence on critical system components. For example, algal population density and herbivore density affect grazing intensity (McMahon and Rigler 1965; Lehman 1980a); temperature and light intensity influence sinking rates (Burns and Rosa 1980); and algal population density and environmental conditions may affect disease incidence (Shilo 1971).

91. Sinking of algal cells out of the mixed layer can lead to significant population losses, especially for large diatoms such as <u>Asterionella</u> and <u>Melosira</u> (Lund 1959, Reynolds 1976b, Lewis 1978). Reynolds (1976a) estimated that <u>Fragellaria</u> population losses due to a sinking rate of 0.5 m/day amounted to approximately 10 percent of the population per day. On the other hand, Jassby and Goldman (1974)

calculated that sinking could account for an average loss of only 0.004 of the phytoplankton standing crop per day in Castle Lake, California.

92. Sinking losses are incorporated into a general mass conservation equation expressing phytoplankton gains and losses in three dimensions (e.g., DiToro 1980). Because the mathematical complexities prevent a comprehensive analysis of vertical and horizontal transport processes, the analysis has been reduced to a one-dimensional case; i.e., horizontal gradients are considered negligible compared with vertical and temporal gradients. DiToro (1974, 1980) represents phytoplankton change as:

$$\frac{\partial P}{\partial t} - \frac{\partial}{\partial z} \left(E \frac{\partial P}{\partial z} \right) + \frac{\partial}{\partial z} (wP) = (G-D)\ P \qquad (23)$$

where:

P = concentration of phytoplankton biomass

z = vertical coordinate direction

E = dispersion coefficient

w = vertical transport velocity (i.e., sinking rate when negative)

G = population growth rate

D = population death rate

93. In general, the presently available models of phytoplankton dynamics do not consider sinking processes adequately (Park and Collins 1980; Lorenzen et al. 1980). Sinking rate is a function of cell shape, surface area to volume ratio, organism density, cell surface chemistry, and the viscosity and turbulence of the surrounding medium (Hutchinson 1957; Smayda 1970). Most of these cell characteristics are affected by physiological state. Titman and Kilham (1976) have shown that nutrient depletion leads to increased sinking rate. Cells taken from a stationary phase culture sink significantly faster than those obtained from exponential phase of growth (Smayda 1974; Titman and Kilham 1976). The general model of Scavia et al. (1976) may be the only one that accounts for physiological influences on sinking rates (Park and Collins 1980). Most general models incorporate a constant sinking rate only.

94. Although a quantitative analysis of the effects of artificial circulation on algal sinking rates is lacking at this time, several qualitative predictions can be stated. First, decreases in epilimnetic temperatures brought about by artificial mixing will increase water viscosity and lessen sinking from the upper water layer. Since such temperature decreases are small (Toetz et al. 1972; Pastorok et al. 1980), this effect will probably be negligible. Temperature increases in lower waters due to destratification are significant however, leading to a prediction of increased rates of sinking from the euphotic zone. Nevertheless, induced turbulence which helps to maintain algal cells in suspension will almost certainly override any influence of temperature shifts. Finally, it should be noted that blue-green algae have a special buoyancy-regulating mechanism (e.g., Reynolds 1972, 1973), making it impossible to predict effects of mixing on sinking losses for this group.

95. Although formulations for grazing influences on phytoplankton have not yet been incorporated into models of artificial destratification, considerable theoretical analysis of zooplankton-phytoplankton interactions has been accomplished (review in Lehman 1980a). The components of zooplankton grazing include ingestion, assimilation, respiration, excretion, egestion, and allocation of energy and nutrients to maintenance, growth, and reproduction. Lehman (1980a) presented typical formulations for each of these processes. He concluded that comprehensive models of zooplankton dynamics are presently rare. Most models fail to incorporate population size structure, age structure, and other life history characteristics.

96. Aeration should allow zooplankton to occupy the entire water column. In the absence of treatment, zooplankton may be restricted to the upper waters of a eutrophic reservoir because of anoxic conditions in the hypolimion (Fast 1971b; Heberger and Reynolds 1977; Brynildson and Serns 1977). Some coldwater species such as *Daphnia longiremis*, which is usually found in the hypolimnion, may be eliminated at the time of oxygen depletion (Heberger and Reynolds 1977). Artificial aeration should allow such species to persist throughout summer, unless temperature intolerence is a factor.

97. Because artifical mixing initially dilutes phytoplankton and zooplankton populations, grazing intensity will decline immediately as a result of lower food concentrations. Eventually,

zooplankton grazing may increase following artificial mixing due to: (a) higher zooplankton abundance upon relaxation of fish predation; (b) higher ingestion rates due to invasion of more efficient grazers; (c) higher zooplankton abundance due to increased food or alternative food resources; and (d) higher ingestion rates because of the shift toward a more edible algal resource.

98. By oxygenating bottom waters, artificial aeration extends habitat for both zooplankton and fish, distributing their numbers throughout a greater water volume compared to before treatment. Moreover, dark bottom waters serve as a prey refuge, protecting zooplankters from visual predators which depend on relatively high light levels for efficient feeding (Zaret and Suffern 1976; Jacobs 1978). Reduction in encounter rates between fish and zooplankton lessens predation pressure and allows population growth and invasion of large-bodied zooplankton (Hrbacek et al. 1961; Andersson et al. 1978; DeBernardi and Giussani 1978). Since ingestion rate is size-related, large species such as Daphnia are more effective at controlling algal populations than are small zooplankters (Haney 1973; Hrbacek et al. 1978). Because they release less phosphorus per unit body weight than smaller forms do (Bartell and Kitchell 1978), large zooplankton species recycle less nutrients for use by phytoplankton.

99. Two other factors could elevate zooplankton abundance after artificial circulation. Mixing often resuspends organic detritus from bottom sediments. Although this material would be refractory in general, it could serve as an important alternative food resource (Saunders 1972). A shift from blue-green algae to green algae often accompanies mixing experiments (see below). Blue-green algae are generally inedible and sometimes toxic to zooplankton (Arnold 1971; Porter 1973; Webster and Peters 1978; Porter and Orcutt 1980). Green algae are usually a preferred food resource, although some large species may be unaffected by grazing. Gelatinous greens may actually increase population growth in the presence of grazers (Porter 1975, 1976). In general, both green algal dominance and provisioning of detrital food resources should favor increased zooplankton abundance.

100. The experiments of Andersson et al. (1978) illustrate the possible impact of fish on phytoplankton-zooplankton interactions. They found that dense fish populations released nutrients and kept planktonic cladocerans at low population levels, causing blooms of

blue-green algae. In experimental enclosures without fish, large cladocerans prospered and grazed the phytoplankton down to low levels.

101. The ultimate effect of artificial mixing on phytoplankton-zooplankton interactions may depend on the physical-chemical milieu and successional time scale. The selective effect of grazers is well known (Porter 1973, 1977; Lynch 1979; also see below), and removal of favored food species may actually lead to domination of the phytoplankton assemblage by grazer-resistant forms. Depending on other environmental conditions, these may be blue-greens, dinoflagellates, or gelatinous greens. In any event, if a successional sequence is driven by intense grazing pressure, the end result could be a bloom of undesirable algae.

102. Parasitic fungi, bacteria, and viruses are capable of causing substantial mortality in phytoplankton populations. Wetzel (1975) postulated that parasitism increases in eutrophic waters. The best documented cases of fungal infections in phytoplankton are the studies in the English Lake District by Canter and Lund (1948, 1969). Chytrid fungi were responsible for significant reduction of the dominant desmids, and in combination with low nutrient levels they led to the decline of diatoms (Asterionella). Although host-specific parasites would be expected to modify competitive interactions between phytoplankton species, seasonal patterns of algal succession were apparently unaffected by fungal infections in the English Lake District.

103. Bacteria and viruses frequently colonize healthy blue-green algae (Shilo 1971) although stressed cells, particularly those growing under low nutrient conditions, may be even more susceptible to infection (Jones 1976). DePinto (1979) presents a comprehensive review of colonization processes and mortality due to parasites and disease.

104. In general, little progress has been made in modeling parasitic phenomena, although some investigators have included the effects of disease-related mortality implicitly (cf. Park and Collins 1980). None of the models of artificial destratification have included specific formulations characterizing the behavior of parasite-phytoplankton systems. There seems little reason to believe a priori that whole lake mixing should affect the incidence of disease or parasites in plankton populations. However, empirical evidence

suggests that mixing may produce pH conditions favorable to the invasion of cyanophages; viruses specific to blue-green algae (Shapiro et al. 1975). Since the selective effects of disease have a profound influence on phytoplankton species composition, this information will be discussed more fully below.

105. Peak biomass vs. mixed depth. Accurate predictions of peak algal biomass based on depth of the mixed layer depend on realistic models which incorporate terms for all potentially significant factors regulating photosynthetic gains and biomass losses: *light, nutrients, respiration, grazing, sinking, and disease.* Early models concentrated on the effects of light on algal production (e.g., Sverdrup 1953; Murphy 1962; Vollenweider 1965). Bella (1970) added the effect of sinking rate on loss of algal cells from the mixed layer.

106. Oskam (1973, 1978) modified Vollenweider's (1965) basic equation to include respiration as well as incremental attenuation coefficients due to light absorption by phytoplankton. After obtaining an expression for net photosynthesis as a function of maximum photosynthetic rate, light intensity, and mixed depth, the *steady-state concentration of algae*, C_{max} (mg Chl m^{-3}) is found by setting the photosynthesis equation equal to zero and rearranging. Thus:

$$C_{max} = \frac{1}{\varepsilon_c} \left[\frac{F(i) \cdot \lambda}{24r \cdot z_m} - \varepsilon_w \right] \tag{24}$$

where:

$F(i)$ = dimensionless function of light intensity
λ = daylight hours
r = ratio of respiration and photosynthesis at optimum light
z_m = mixing depth (m)
24 = hours per day

and other terms are defined above. Note that nutrient effects and biomass losses other than those due to respiration are not incorporated into Oskam's model. Based on Equation 23, and assumming numerical values of ε_c = 0.02, $F(i)$ = 2.7, λ = 12, and r = 0.05 (Oskam 1978), Figure 2 shows the relationship between maximum algal biomass

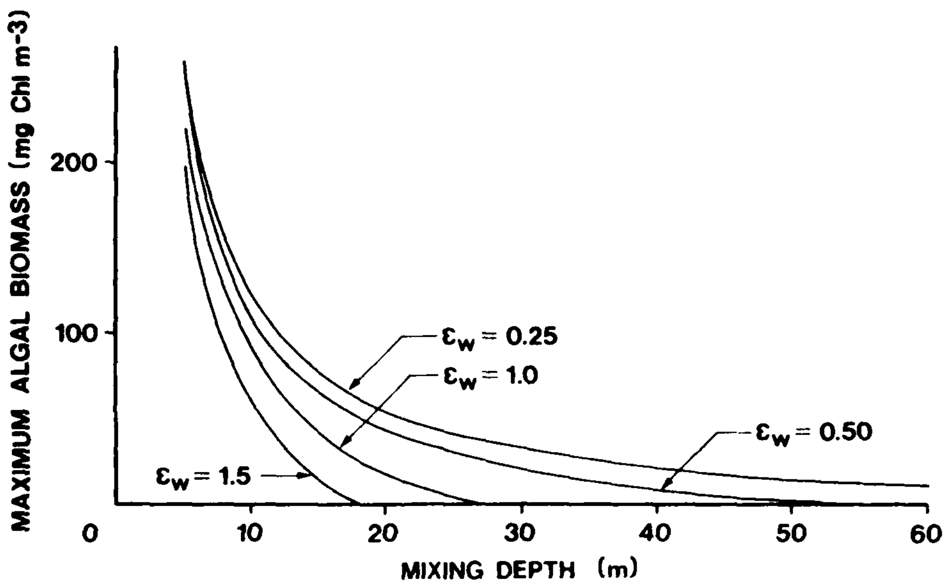


Figure 2. Relation of maximum chlorophyll concentration to mixing depth for different levels of non-algal attenuation of light (adapted from Oskam 1978).

and mixed depth for different levels of nonalgal attenuation of light.

107. Lorenzen and Mitchell (1973, 1975) followed a similar approach and found that peak algal biomass limited by light was given as:

$$CZ = \frac{K_{max}}{R\varepsilon}\left[\frac{1}{\Delta T}\int_0^{\Delta T} \ln\left(AI_0(t) + \left\{1 + [AI_0(t)]^2\right\}^{1/2}\right) dt\right] - (\alpha/\beta)Z \qquad (25)$$

This implies an inverse linear relation between light-limited biomass and mixed depth with the line having a slope of $-\alpha/\beta$ (Figure 3). A separate expression (see above Equation 20) is used to relate peak nutrient-limited biomass to mixed depth, giving a straight line with positive slope equal to the capacity of the system to produce algal biomass before nutrients are depleted.

108. Although the model of Lorenzen and Mitchell (1973, 1975) ignores the effects of mixing on algal losses by sinking, grazing, and parasitism, it places an upper bound on predicted levels of biomass developing under a variety of circumstances. From Figure 3, one predicts that artificial mixing will have opposite results in lakes where different factors limit phytoplankton growth. For example, if algae are limited by nutrients before artificial circulation, a slight increase in mixing depth could cause an elevation of standing crop (e.g., point A to point B in Figure 3), a result opposite to that found in the light-limited case (e.g., C to D in Figure 3).

109. When mixing shifts the controlling mechanism from nutrient limitation to light limitation, a moderate increase in mixed depth will cause a substantial rise of peak algal biomass or at best only a slight decline (A to C or B to C, respectively, in Figure 3). For large increases in mixed depth, however, the imposition of light limitation can cause substantial decreases in areal algal biomass (B to D in Figure 3). It should be noted that when water column biomass decreases with a deepening of the mixed layer, the concentration of algae will decrease dramatically because less biomass is distributed in a much larger water volume. In any event, since the slope of the ascending curve in Figure 3 equals the capacity of the system to produce algae, the slope for oligotrophic lakes will be smaller than that for eutrophic lakes. Therefore, any given change in mixed depth

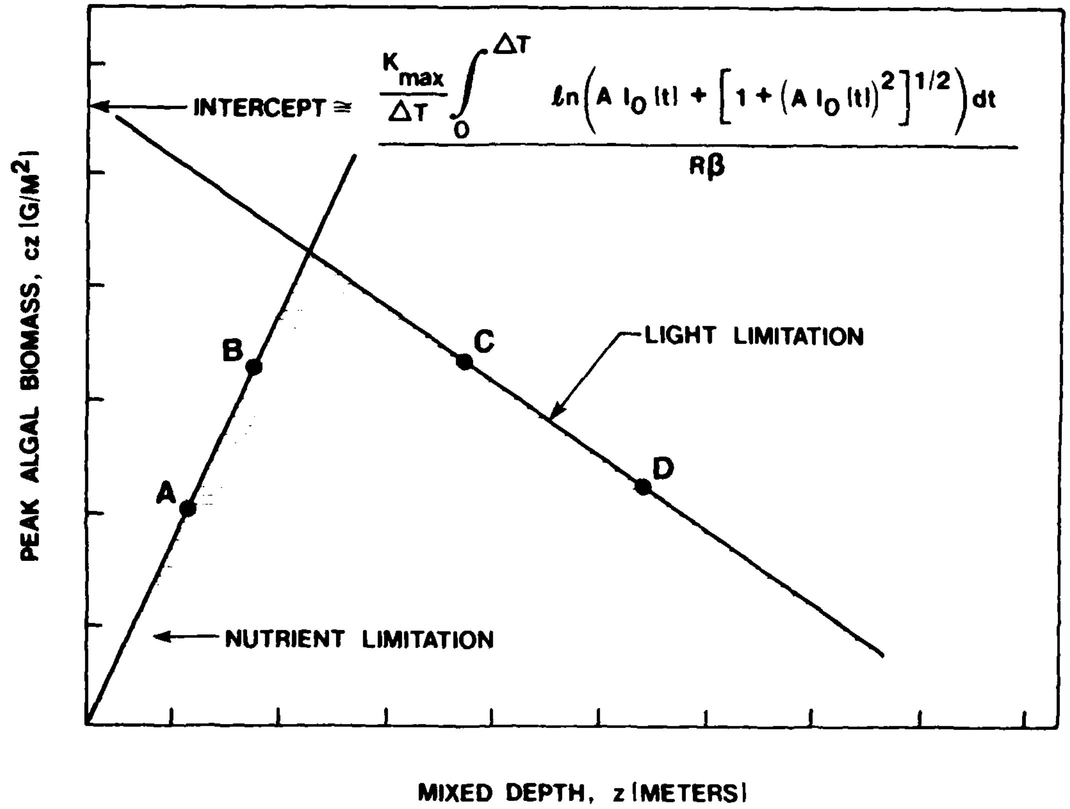


Figure 3. Generalized plot of peak algal biomass as a function of mixed depth for both nutrient and light limitations (adapted from Lorenzen and Mitchell 1973, 1975).

over the range of nutrient-limited biomasses should result in only small displacements of standing crop in oligotrophic lakes compared with potential shifts in richer lakes.

110. Instead of treating nutrient limitation and light limitation separately, Forsberg and Shapiro (1980a) have combined Equation 17 and Equation 22 to incorporate both light and nutrient effects into a single expression for peak chlorophyll a concentration (C*) in the mixed layer:

$$C^* = \frac{\ln(I_o/I_{z'})\, P^s_{max} - \epsilon_w Z_m \Theta D}{\epsilon_c Z_m \Theta D - (\ln(I_o/I_{z'}) P^s_{max} k'_q) / S_o} \qquad (26)$$

where:

Θ = ratio of carbon to chlorophyll a in the algae (mg C mg Chl^{-1})

D = specific loss rate (day^{-1})

Z_m = depth of the mixed layer (meters)

Figure 4 shows the dependence of peak algal concentration and biomass on mixed depth and total phosphorus.

111. Based on Equation 18 above, Stefan et al. (1976) have calculated the depth-integrated biomass of phytoplankton in the mixed layer of Halsted's Bay, Lake Minnetonka from May through October (Figure 5). They compared natural phytoplankton levels with model calculations based on artificially mixing the lake to 6-m and 9-m depths. The simulations showed that increasing the mixed depth stabilized phytoplankton biomass at low levels compared to the natural condition (Figure 5).

112. Limitations of theory. The following considerations place limits on the precision and reality of models relating phytoplankton growth rate and biomass to mixed depth:

a. Failure to incorporate explicit terms for temperature dependence of some processes.

b. Adaptation of algae to past conditions; for example, nutrient uptake rates change with previous nutritional history and relations between photosynthetic rate and light intensity depend on recent exposure.

c. Variation of the algal extinction coefficient (β) with depth, water color, and algal species (Atlas and Bannister 1980).

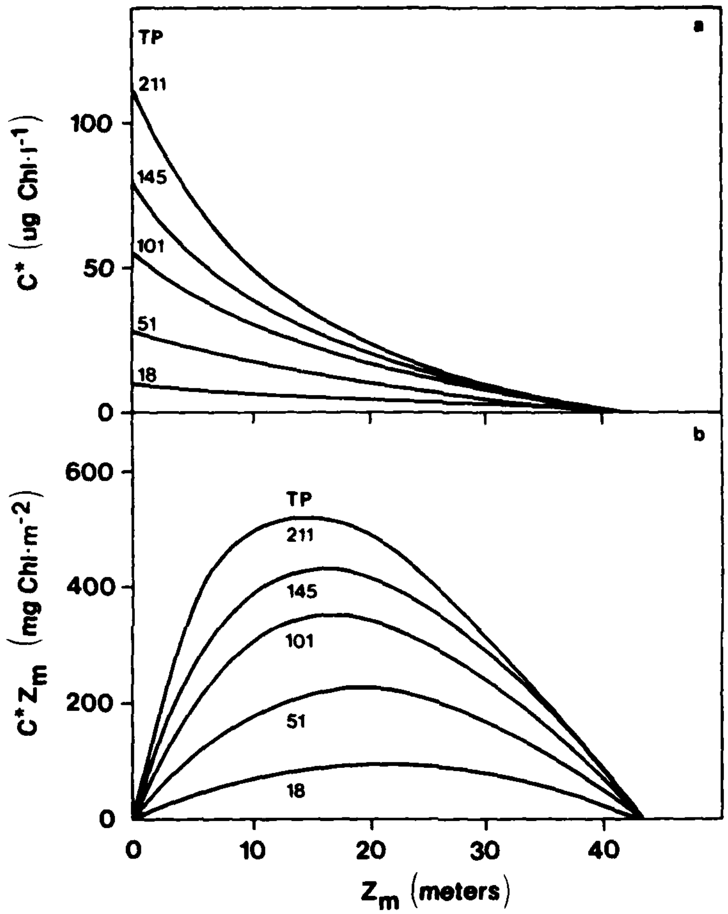


Figure 4. Relation of peak chlorophyll concentration (C*) and areal biomass (C^*Z_m) to mixed depth (Z_m) and total phosphorus (TP).
(adapted from Forsberg and Shapiro, 1980b).

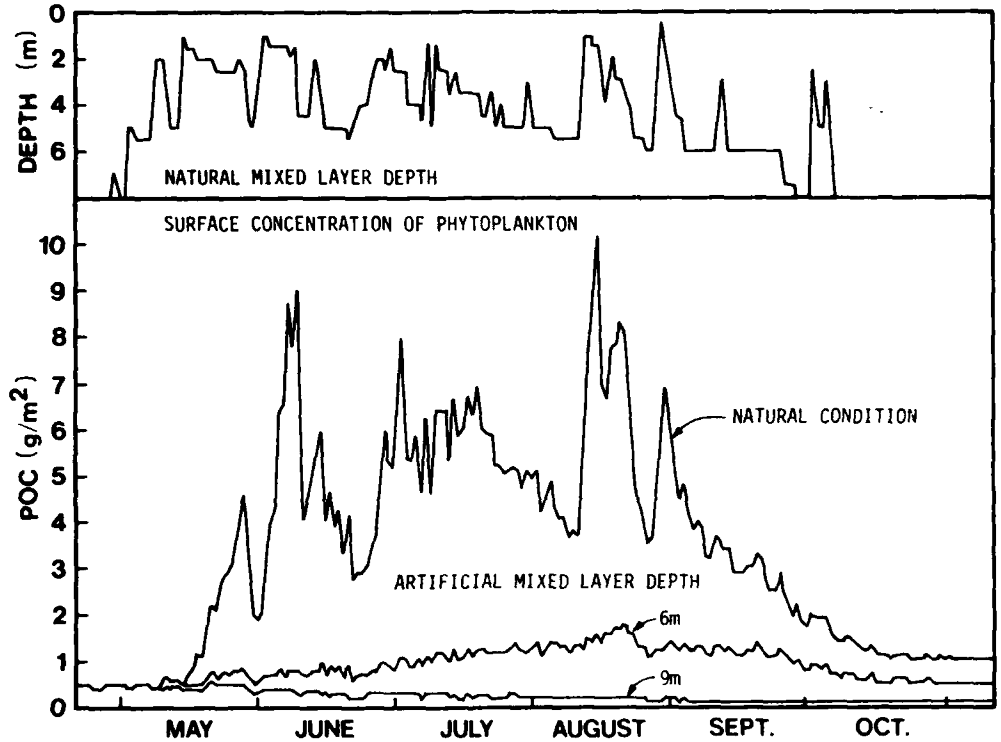


Figure 5. Seasonal variation of calculated mixed layer depths and integral phytoplankton biomass in the mixed layer (from Stefan et al. 1976).

d. Difficulties of obtaining field estimates of some parameters; e.g., sinking rates, light intensities.

e. Variations of algal community responses with shifts in species composition (Forsberg and Shapiro 1980a, b).

f. Model assumptions require that phytoplankton be uniformly distributed throughout the mixed layer.

g. Interactions among factors limiting algal growth, e.g., light, phosphorus, and carbon dioxide availability (Young and King 1980).

Phytoplankton: species composition

113. Artificial circulation changes the species composition of the phytoplankton through physical, chemical and/or biological modifications which shift the balance of population gains and losses. These effects may include direct disruption of individual species distributions, physical damage to cells, or indirect environmental modifications leading to competitive imbalance, differential sinking rates, selective grazing or selective parasitism. Quantitative models of algal species interactions have not yet been applied to problems of artificial destratification.

114. Disruption of vertical profile. Some phytoplankton, expecially blue-green species, occupy discrete depth layers in lakes, probably to take advantage of favorable light, temperature, and/or nutrient conditions. For example, *Oscillatoria* species often exhibit a metalimnetic population maximum (Bernhart 1967; Weiss and Breedlove 1973; Smith et al. 1975), usually near the bottom of the euphotic zone (Reynolds and Walsby 1975). Other phytoplankton species, such as the dinoflagellate *Ceratium hirundinella*, exhibit diel vertical migrations (Talling 1971; Burns and Rosa 1980). Presumably, their movements from one water layer to another allow them to exploit various resources available at different points along spatial and temporal gradients. For example, *Ceratium* may absorb dissolved nutrients from rich hypolimnetic waters at night and utilize high light levels available in the epilimnion during the day (Reynolds and Walsby 1975).

115. Artificial mixing will destroy vertical gradients in temperature and nutrients, subjecting the phytoplankton assemblage to a more homogeneous environment. Deep circulation may therefore select against those species which exploit specific microhabitats or exclusive resources. Under the less favorable conditions accompanying mixing, such populations may fail to grow rapidly enough to balance population losses. In the face of interspecific competition, they may be excluded by faster-growing generalists.

116. Hydrostatic damage. Most blue-green species control their vertical position in the water column by buoyancy regulation achieved through changes in size, number, and content of gas vesicles (Fogg and Walsby 1971; Reynolds and Walsby 1975; Konopka et al. 1978). Artificial mixing could collapse the gas vesicles by rapidly circulating cells into a zone of high hydrostatic pressure. Once collapsed, a gas vesicle cannot be restored, but new ones can form to regain cell buoyancy (Reynolds and Walsby 1975). Continuous circulation throughout a wide range of depths could prevent reforming of vacuoles however. Under these conditions, the ability of blue-greens to compete with other algal species might suffer. Even if cells remain viable after gas vacuole collapse (Reynolds and Walsby 1975), they temporarily lose the ability to "select" desired depths.

117. The "critical pressure," i.e., that pressure leading to vesicle collapse, varies from about 3 to 7 atm for vesicles isolated from Anabaena flos-aquae (Walsby 1971) to about 11 atm for Oscillatoria agardhii (Walsby and Klemer 1974). A pressure equivalent to 7 atm would be attained at about 55 m, and 11 atm at about 100 m. Thus, artificial mixing in relatively deep lakes could transport cells to depths where ambient pressures exceed critical values for gas vacuole collapse. In shallower lakes, hydrostatic damage to cell vacuoles would probably be of little importance.

118. The role of acclimation in allowing cells to withstand extreme pressures is unclear. Since the hollow space of a gas vacuole is maintained by the rigidity of the walls of the vesicles (Reynolds and Walsby 1975), acclimation should depend on protein synthesis and thickening of the vesicle walls. Although several days might be required to mix an originally stratified population to depths greater than 55 m, the acclimation powers of algae have not been studied.

119. It is also possible that gas vesicles could be ruptured by excess internal pressure, generated by rapidly mixing algae through zones of differing hydrostatic pressures. At present, the importance of this mechanism remains unknown.

120. Competition. Artificial circulation may affect competitive interactions among phytoplankton species by modifying habitat conditions or nutrient and light resources. Resultant shifts in species composition will follow competitive imbalances produced by changing environments. Competitive displacement may be effected

through differential growth related to species-specific optima within light and temperative gradients (Aruga 1965), differential nutrient requirements and nutrient uptake kinetics (Titman 1976; Tilman 1977), and allelopathic inhibition (Keating 1977, 1978). Selective loss factors (e.g., grazing, sinking, etc.) may actually be more important than differential growth as the driving force for seasonal succession of species (Hutchinson 1957; Knoechel and Kalff 1975; Kalff and Knoechel 1978).

121. After rapid mixing, competition may be temporarily relaxed due to the increase in available nutrients compared to precirculation conditions in the epilimnion. Eventually, nutrients may again be depleted and competitive interactions will intensify within the relatively homogeneous environment of a strongly mixed lake.

122. King (1970a) has suggested that blue-green algae dominate the phytoplankton of enriched lakes because they are efficient at taking up carbon at low ambient CO_2 concentrations and high pH. Green algae are generally less able to extract CO_2 from water at high pH. Moreover, blue-green algae would also be favored under conditions when phosphorus and nitrogen are in short supply. The half saturation constant for phosphate uptake is lower for blue-green algae than it is for green algae, indicating faster uptake by blue-greens at low nutrient concentrations (Shapiro 1973). Their ability to fix nitrogen guarantees most species of blue-greens a supply of that essential nutrient as well.

123. As Shapiro (1973; Shapiro et al. 1975) has pointed out, destratification adds CO_2 to photic zone waters by mixing hypolimnetic waters into the upper layer and by promoting reaeration through atmospheric exchange. In addition, phosphates accumulated in the hypolimnion during thermal stratification will be at least partly mixed throughout the lake. Circulation therefore removes the competitive advantages previously enjoyed by blue-green species. Artificial circulation should also mitigate chemical interference by blue-greens (Keating 1977, 1978). Mixing would immediately dilute any blue-green toxins which potentially inhibit growth of competitors.

124. Several quantitative models of phytoplankton competition are available for evaluation of species coexistence (e.g., Peterson 1975; Tilman 1977; Kemp and Mitsch 1979), although none has been applied to prediction of destratification effects. Peterson (1975)

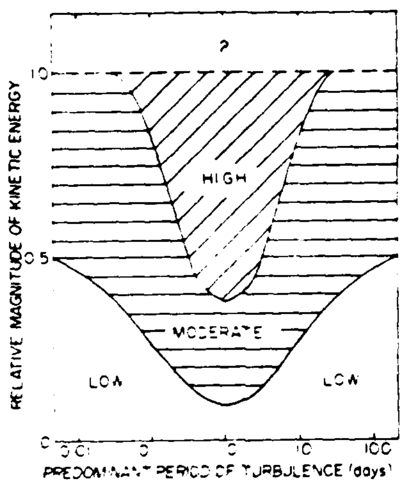
analyzed the case of multiple limiting resources for three phytoplankton species. When nutrient requirements of the species differed from one another sufficiently, coexistence of all three species was possible. Thus, divergence of species-specific requirements might be expected over time. Effects of destratification on the number of potentially limiting nutrients are unknown however.

125. Grenney et al. (1973) modeled the influence of environmental fluctuations on interspecific competition in the phytoplankton communities of rivers. Changes in nutrient availability were related to variations of flow regime. Step-wise changes in flow simulating dilution or concentration of nutrients represented an environmental disturbance which allowed coexistence of species if the period between changes was large enough. Although their model is not directly applicable to destratification, it does suggest that periodic disturbance of physical-chemical gradients increases species diversity in phytoplankton.

126. Kemp and Mitsch (1979) used a simulation model to investigate the relation between water turbulence and phytoplankton diversity in a given water parcel. Species coexistence on a single limiting nutrient was possible only under turbulent regimes. All three species persisted over the 30-day model run at turbulence periods centered around 1 day, a reasonable value for natural lakes (Figure 6). Moreover, the periodicity of physical disturbance required for coexistence of all three species was on about the same order as the turnover time for each of the species.

127. In Kemp and Mitsch's (1979) model, turbulence is linked to phytoplankton dynamics in two counteracting ways. First, water movements enhance nutrient-depleted water near algal cell surfaces. This avoids excess loss of energy in active transport or motility. Secondly, turbulence increases respiratory losses and reduces photosynthetic rate, in part because of increased diffusion of respiratory products with water movement and in part from stress effects on cells.

128. If natural levels of turbulence lessen the intensity of competitive interactions and permit high species diversity, then intense artificial mixing might disturb species coexistence by reducing the period of turbulence (i.e., moving to the left in Figure 6). The exact position of an artificially mixed lake on Figure 6 is



Cross-hatched area indicates high plankton diversity (three species coexisting

Horizontal-hatched area indicates moderate plankton diversity (two species coexisting)

Open area indicates low diversity (only one species survives)

Area above kinetic energy of 1.0 is untested since that is beyond the realistic design limits of the model (from Kemp & Mitsch 1979).

Figure 6. Schematic representation showing regions of species coexistence for different combinations of magnitude and periodicity of hydrodynamic kinetic energy.

unknown, however. Since Kemp and Mitsch (1979) did not specify absolute levels of kinetic energy, the effects of induced circulation on diversity remain unclear from their model. If phytoplankton characteristics are keyed to periodicities of physical energy, one expects shorter population turnover times after artificial mixing because of a decreased period of turbulence relative to the natural state (Kemp and Mitsch 1979). Since cell size is inversely related to turnover time (Kalff 1971; Gelin 1975), small cells should predominate following artificial circulation.

129. Kemp and Mitsch (1979) showed that moderate turbulence may generate species diversity within a single parcel of water. However, a natural lake consists of many temporary water patches. The natural rate of mixing is slow enough relative to algal reproductive rates for many different niches to exist simultaneously. In any given patch, one species is at a competitive advantage relative to the rest, but the identity of the superior competitor differs among patches. The water patches are stable enough to form a heterogeneous environment which encourages diversity, but mixing obliterates individual niches frequently enough to prevent a single species from dominating within each one. Thus, a "cotemporaneous disequilibrium" exists among phytoplankton patches (Richerson et al. 1970).

130. Intense artificial circulation would be expected to inhibit development of alternative communities in temporary niches. Along with destruction of vertical stratification, strong circulation would reduce habitat heterogeneity on a horizontal scale. The expected result is an overall decline in phytoplankton species diversity.

131. Differential sinking rates. After reviewing the hydromechanics of plankton, Hutchinson (1957) concluded that much of the seasonal succession of phytoplankton is probably controlled by the interaction between turbulence and species-specific sinking velocities. Knoechel and Kalff (1975) investigated the replacement of *Tabellaria fenestrata* by *Anabaena planctonica* in Lac Hertel (Quebec). They found that the summer decline of the diatom resulted from a high sinking rate rather than reduced production. Despite a low growth rate, *Anabaena* continued to increase and become dominant, probably because of a much lower sinking rate.

132. Under calm conditions in the epilimnion, phytoplankton must possess special adaptations to reduce sinking rate; e.g., small size,

projections, motility (Hutchinson 1957; Wetzel 1975). Mixing helps maintain cells in suspension and therefore removes selective pressure towards development of floatation devices. Artificial circulation should favor those phytoplankton which lack special buoyancy adaptations and would be susceptible to rapid sinking in a stratified lake (Steel 1972; Lackey 1973a). This argument is based on the hypothesis that some fitness loss (e.g., energetic cost; reproductive loss) is associated with possession of special adaptations for floatation. Such adaptive features will therefore represent a liability in a well-mixed lake; and their possessors may be outcompeted by species with higher growth rates or defenses against grazers.

133. Based on reviews of marine phytoplankton by Smayda (1970) and freshwater phytoplankton by Hutchinson (1957), Table 1 gives examples of morphological and behaviorial characteristics which aid suspension.

134. In addition, various cell shapes may reduce settling velocity, but their effects are cell-size dependent (Munk and Riley 1952). For particles 5 μm in diameter, plate > cylinder > sphere (in order of decreasing sinking rate). For those 50 μm in diameter, cylinder = plate > sphere. And for 500 μm particles, cylinder > sphere > plate. When the interactions of nutrient uptake, sinking rate, and turbulence are taken into account, the spherical shape has a large adaptive advantage over the cylindrical form. A discoid-shaped cell (e.g., many diatoms) would probably be similar to the sphere (Hutchinson 1957). The influence of grazing may negate the differential adaptive values of these various shapes, however (Munk and Riley 1952). Further work in this area is necessary before firm predictions can be made.

135. Under turbulent conditions, small cell size might still be advantageous where nutrient concentrations are low. Small size increases the ratio of cell surface area to volume, allowing more effective uptake of nutrients. If remaining in suspension is not a problem, e.g., during artificial mixing, the other adaptations listed in Table 1 are disadvantageous because they demand energy for production and maintenance. Moreover, gelatinous sheaths may interfere with nutrient uptake by creating an additional diffusional barrier (Wetzel 1975). Of course, some adaptations such as gelatinous

TABLE 1. PHYTOPLANKTON SUSPENSION CHARACTERISTICS

Characteristic	Example
Small size	Nanoplankton: *Chlorella*, *Rhodomonas*, *Chromulina*, *Mallomonas*
Form resistance - elongations	*Tabellaria*, *Synedra*, *Navicula*, *Diploneis*
- projections	*Staurastrum*, *Ceratium*, *Chaetoceros*
Gas vacuole	Most blue-green algae: *Aphanizomenon*, *Anabaena*, *Oscillatoria*, *Microcystis*, *Lyngbya*
Gelatinous sheath	Most blue-green algae; gelatinous green algae: *Sphaerocystis*, *Elakatothrix*, *Eudorina*
Fat accumulation	*Botryoccocus*
Motility	Flagellates: *Ceratium*, *Cryptomonas*, *Dinobryon*, *Synura*, *Volvox*

sheaths and cell projections may serve both for floatation and defense against grazers (Dodson 1974; Porter 1977). In this case, their occurrence will not be closely linked with turbulence in the environment. On the other hand, large cell size confers resistance to grazing but it also increases sedimentation rate.

136. Smayda (1970) hypothesized that morphological adaptations are not floatation aids, per se, but mechanisms to produce rotation or vertical movements. He viewed the problems of marine phytoplankton in terms of nutrient assimilation and light orientation constraints rather than sinking characteristics. Nevertheless, protected freshwater lakes are apt to be less turbulent environments than the ocean; high sinking losses are a well-documented problem for freshwater phytoplankton (Knoechel and Kalff 1975; Lehman and Sandgren 1978; Kalff and Knoechel 1978).

137. Table 2 summarizes literature data on sinking rates of freshwater phytoplankton. It is difficult to compare data from different investigators because of variations in measuring techniques and experimental temperatures. Recognizing the limitations in such an approach, the mean sinking rate was calculated for various algal groups based on measurements taken at 15-21° C (including data of Kalff and Knoechel (1978) for which field temperatures were not given). These data suggest the following rank order of sinking rates: diatoms > flagellates $\geq$ greens > blue-greens (Table 3). The results of Burns and Rosa (1980), the only study which included all four groups, suggests a similar ranking: diatoms $\geq$ flagellates > greens > blue-greens (Table 2).

138. Lewis (1978) analyzed population dynamics of phytoplankton in Lake Lanao in relation to the intensity of turbulent mixing. There was a strong tendency for blue-green algae and dinoflagellates to dominate the plankton when turbulence was minimal. Diatoms and cryptomonads grew best when turbulence was maximal, probably because these forms rely on mixing to keep them in suspension. Green algae occupied a broad range of conditions between the environmental extremes. In general, these findings are in agreement with settling velocity rankings based on data in Tables 2 and 3.

139. Grazing effects. Selective grazing can have a profound influence on phytoplankton assemblages (Gliwicz 1975; Porter 1977; Lynch 1979). Lake zooplankton filter and ingest cells within the 1-10

TABLE 2. SINKING RATES OF FRESHWATER PHYTOPLANKTON

Taxon	Data Source	Mean Diameter (μm)	Temperature (°C)	Sinking Rate (m/day) Mean	±95% CL	Range	Reference
Asterionella formosa	lab + field	(30-140)[a]	0	0.19		0.07-0.84	Lund 1959
Melosira italica	lab + field	(8-21)	0	0.90		0.52-2.10	
Cyclotella meneghiniana	lab-exp[b]	2	20	0.08	±0.10		Titman and Kilham 1976
Cyclotella meneghiniana	lab-sta[c]	2	20	0.24	±0.31		
Scenedesmus quadricauda	lab-exp	8.4	20	0.27	±0.04		
Scenedesmus quadricauda	lab-sta	8.4	20	0.89	±0.06		
A. formosa	lab-exp	25	20	0.20	±0.06		
A. formosa	lab-sta	25	20	1.48	±1.05		
Melosira agassizii	lab-exp	54.8	20	0.67	±0.48		
Melosira agassizii	lab-sta	54.8	20	1.87	±0.38		
Green algae	field					1-3	Schnoor and DiToro 1980
Blue-green algae and phytoflagellates	field					<0.1	
Diatoms	field					0.1-1.0	
A. formosa	lab-exp	(30-140)	20	~0.2			Titman 1975
A. formosa	lab-sta	(30-140)	20	~1.2			
A. formosa	lab-exp	(30-140)	15	0.26			Smayda 1974
A. formosa	lab-sta	(30-140)	15	0.32			
Tabellaria flocculosa	lab-sta	(12-50)	15	0.39			
Cryptomonas erosa	field		20	0.31	±0.32		Burns and Rosa 1980
Cryptomonas marsonii	field		20	0.32	±0.32		
Rhodomonas minuta	field		20	0.07	±0.21		
Fragilaria crotonensis	field	(40-150)	20	0.27	±0.13		
Gomphosphaeria lacustris	field		20	0.11	±0.05		
Anabaena spiroides	field		20	-0.10	±0.11		
Selenastrum minutum	field		20	0.15	±0.13		
Closterium parvulum	field		20	0.18	±0.11		
Scenedesmus acutiformis	field		20	0.10	±0.06		
Lagerhaemia quadriseta	field		20	0.08	±0.11		

(Continued)

Table 2. (continued)

Taxon	Data Source	Mean Diameter (um)	Temperature (°C)	Sinking Rate (m/day) Mean	95% CL	Range	Reference
Tabellaria fenestrata	field	(30-140)	22-26	0.30		~0-0.85	Knoechel and Kalff 1975
Cyclotella bodanica	lab	49	6	1.4			
Cyclotella bodanica	lab	49	20	1.9			
Asterionella formosa	lab	68	6	0.7			Fritz 1935 in Smayda 1974
Asterionella formosa	lab	68	20	1.0			
Fragilaria crotonensis	lab	68	6	0.5			
Fragilaria crotonensis	lab	68	20	1.0			
Tabellaria	lab		17-18			1.7-3.9	Grim in Hutchinson 1957
Fragellaria crotonensis	field	(40-150)	~9-19	0.43		0.06-0.87	Reynolds 1976a
Melosira granulata	field	(5-21)	~11-15	0.96		0.17-2.01	Reynolds 1976a, b
Synedra radians	field			0.51			
Asterionella formosa	field	(30-140)		1.53			
Melosira italica	field	(8-21)		0.95			Kalff and Knoechel 1978
Fragilaria crotonensis	field	(40-150)		0.76			
Tabellaria fenestrata	field	(30-140)		0.87			
Scenedesmus acuminatus	lab		21	0.26	±0.13		
			15	~0.16			
			10	~0.14			
			5	~0.09			
Chlorella vulgaris	lab		21	0.14	±0.05		Stutz-McDonald and Williamson 1979
Microcystis aeruginosa	lab		21	0.13	±0.11		
			15	~0.09			
			10	~0.07			
			5	~0.02			

[a] Values in parentheses are greatest cell dimension taken from Weber (1971).

[b] Exponential growth phase culture.

[c] Stationary growth phase culture.

TABLE 3. MEAN SINKING RATES OF FRESHWATER PHYTOPLANKTON BETWEEN APPROXIMATELY 15 AND 21° C

	Field Data						Lab Data					
	Sinking Rate (m/day)			Temperature (°C)			Sinking Rate (m/day)			Temperature (°C)		
Algal Group	Mean	Range	N	Mean	Range	N	Mean	Range	N	Mean	Range	N
Diatoms	0.82	0.27-1.53	6	20[a]	-	1[a]	0.77	0.08-1.90	14	18.9	15-20	14
Green algae	0.13	0.08-0.18	4	20	-	4	0.34	0.14-0.89	5	19.4	15-21	5
Flagellates	0.23	0.07-0.32	3	20	-	3	-	-	-	-	-	-
Blue-greens	~0	-0.10-0.11	2	20	-	2	0.11	0.09-0.13	2	21	-	2

[a] Temperature data not available for some sinking rate estimates.

μm size range most effectively (Burns 1968; Gliwicz 1969). Thus, intense grazing will favor larger organisms (or colonies) and forms with cell wall projections to foil handling by herbivores (Dodson 1974). In addition, some algae have special adaptations for defense against grazers; e.g., the gelatinous sheaths of some green algae prevent digestion by herbivores (Porter 1976), and blue-green toxins lead to rejection by grazers or poisoning upon ingestion (Porter 1977; Porter and Orcutt 1980). Within the cell size categories preferred by herbivores, naked green algae and diatoms are generally selected over blue-green species and gelatinous green algae (Porter 1977).

140. The effects of artificial circulation on grazer populations have been described already. Relaxation of grazing pressure immediately after destratification may assist the proposed transition from a blue-green dominated community to a diverse mixture of green algae. With the increase in size structure and total biomass of zooplankton accompanying habitat expansion by herbivores and their predators (planktivorous fishes), grazing intensity may eventually surpass precirculation conditions. In this case, total biomass of phytoplankton may decrease, and grazer-resistant forms will replace preferred algae (i.e., those which are susceptible to herbivores) as dominants in the community.

141. This scenario assumes sufficient time for the successional sequence to progress to completion before seasonal changes in light and temperature depress grazer activity. In some cases there may not be enough time for abundant zooplankton populations to shift the algal assemblage toward resistant species or morphotypes.

142. pH and cyanophage hypothesis. The availability of carbon, phosphorus, and nitrogen regulates the species composition of freshwater phytoplankton to a large extent (Shapiro et al. 1975; DeNoyelles and O'Brien 1978). Direct effects of artificial circulation on pH, nutrient levels and phytoplankton composition have been discussed previously. The pH of water has additional roles in directly determining species distributions and in controlling activity of phytoplankton diseases.

143. Brock (1973) showed that blue-green species are almost completely absent from low pH habitats (pH less than 4 or 5). Eucaryotic species from diverse taxa are distributed over a wide range of pH environments, from pH 1.9 to pH 8.65 in his study. Brock

suggested that low pH was detrimental to the procaryote photosynthetic apparatus; and that blue-green algal blooms should never occur in acid lakes.

144. Using experimental enclosures, Shapiro (1973; Shapiro et al. 1975) has manipulated the species composition of lake phytoplankton by modifying pH conditions. By decreasing pH from 9.5 (i.e., the value in control enclosures) to 7.5 or less, the algal association could be shifted from predominantly blue-green algae to a mixture of small unicellular and colonial green species. As discussed above, Shapiro (1973) originally hypothesized that artificial mixing increased carbon availability by lowering pH of the upper waters and enhancing CO_2 exchange. Coupled with nitrogen and phosphorus increases, the pH shift could break the series of competitive advantages enjoyed by blue-green algae. Later work indicated that green algae slowly replaced the blue-green species after their rapid decline and build up of nitrogen and phosphorus in manipulated enclosures, observations contrary to the competitive mechanism hypothesis (Shapiro et al. 1975). Instead, it appears that cyanophages are activated at neutral or low pH (less than 7.5); they attack blue-greens and decimate entire populations (Shapiro et al. 1975; also cf. Shilo 1971). The exact mechanism for species shifts among the phytoplankton is still uncertain, but recent laboratory experiments have supported the cyanophage hypothesis.*

Fisheries

145. The artificial circulation of lakes may have a profound impact on the abundance and distribution of fish species, individual growth rates, fisheries yields, and species composition of fish communities. Since little attention has been given to modeling the effects of mixing on fish populations, the following discussion will treat fisheries impacts mainly in a qualitative manner.

146. Depth distribution. The seasonal depletion of oxygen in the hypolimnion of a stratified eutrophic lake restricts fishes to the

* Personal communication, J. Shapiro, August, 1980, Limnological Research Center, University of Minnesota, Minneapolis, Minnesota.

warm upper waters. The consequences of eutrophication limit the habitat of fish communities such that coldwater species may be forced to feed in the epilimnion. Compression of vertical living space may necessitate greater partitioning of the habitat resource along a horizontal dimension (e.g., Werner and Hall 1976; Werner et al. 1977).

147. Provisioning of oxygen in deep waters by whole lake mixing allows fish access to all portions of the water column. Artificial destratification of a eutrophic lake should expand fish habitat vertically and facilitate an increase in the depth distribution of fishes. The response to mixing will depend on habitat requirements of the species involved. For example warmwater fishes dependent on littoral habitats for breeding and feeding, e.g., longear, green sunfish, and shiners (Werner et al. 1977), may continue to occupy shallow zones even though thermal conditions in deep waters may be tolerable after mixing. They are therefore expected to exhibit little expansion of habitat following artificial destratification. Coldwater fishes such as trout, on the other hand, should reside in deeper waters as soon as oxygen levels rise above tolerance limits. Brief forays into waters low in oxygen for foraging purposes may be common before more permanent residence is established.

148. Food resources. As mentioned above, the depth distribution and abundance of zooplankton are expected to increase following destratification during spring or early summer. Planktivorous fishes should benefit from enhanced food abundance and availability. Oxygenation of deep waters allows invasion of large-bodied zooplankton (Fast 1971a, 1979a) which find partial refuge from visual predation in dimly lit zones (Zaret and Suffern 1976). Nevertheless, large prey are the preferred food of planktivorous fishes (Brooks and Dodson 1965; Werner and Hall 1974; Eggers 1977); and lakes where large zooplankton abound often serve as quality trout fisheries (Galbraith 1975).

149. Artificial aeration should also allow habitat expansion of benthic prey. In enriched lakes, thermal stratification and hypolimnetic anoxia may restrict many benthic species to the upper littoral zone. Depth distribution, species diversity and productivity of benthic macroinvertebrate communities are all expected to be less in lakes with anoxic hypolimnia than in fully oxygenated waters. On the other hand, some species can survive for months in the absence of

oxygen by using alternate physiological mechanisms. Following aeration of the profundal zone, species tolerant of low oxygen environments may decline due to intensified competition from invading aerobic species or increased predation by fishes. Chaoborus larvae represent a special case among benthic macroinvertebrates because of their unique daily migrations into the limnetic zone in search of food (e.g., Pastorok 1980). Chaoborus species characteristic of eutrophic lakes, e.g., C. punctipennis, find refuge in anoxic lower waters or sediments by day (von Ende 1979). Just before sunset, some individuals move into lighted waters and become increasingly susceptible to capture by visual predators (Northcote et al. 1978). Aeration of the entire water column should increase the temporal and spatial extent of fish foraging and therefore lead to a reduction of prey species dependent on the anoxic profundal refuge.

150. Growth and yield. Given an increase in food abundance and habitat availability, intraspecific and interspecific competition among fishes should be less severe. Artificial aeration should therefore elevate individual growth rates and population yield of fisheries. Niche overlap along the dimensions of habitat and food size/species may also increase (Werner and Hall 1976, 1979). Although essentially no quantitative models have been developed for predicting the effects of artificial mixing on fisheries, it is well known that increased productivity of food organisms leads to faster growth and larger catches of fish (Gerking 1978; Jenkins and Morias 1978; Jenkins 1979). Long-term changes in fish population dynamics and predator-prey equilibria as a result of induced circulation are unpredictable at present.

151. Several investigators have attempted to predict fisheries yield based on average phytoplankton biomass, chlorophyll concentrations, or primary productivity (Ryder et al. 1974; Oglesby 1977). Although these models have not yet been applied to problems of artificial destratification, it may be possible to link changes in higher trophic levels with phytoplankton shifts controlled by mixed depth. That is, models used to predict fisheries yield might be combined with the phytoplankton/mixed-depth models discussed earlier (see "Phytoplankton: production, concentration, and biomass"). In addition, the far-ranging consequences of destratification demand complex modeling incorporating habitat expansion of fishes and their

prey, increases in food resources for higher trophic levels, and shifts in species composition of phytoplankton.

152. Species composition. The most profound changes in species composition of fish communities following aeration/circulation treatment will result from invasion or extinction of coldwater species, especially salmonids. Minimal changes in species composition of warmwater fish commmunities are expected. Invasion of coldwater fishes or distribution into the hypolimnetic zone is possible after mixing of northern lakes. In southern lakes, however, intense solar radiation and distribution of heat throughout the lake by mixing may produce temperatures above the upper tolerance limit. In such cases, invasion of coldwater species is prevented, and extinction of resident populations may occur.

153. The predicted effects of artificial mixing on species composition of fish communities are somewhat similar to a reversal of changes resulting from lake eutrophication. Long-term shifts in species relative abundance have been observed in many lakes following eutrophication. The typical pattern is illustrated by case studies of nutrient enrichment in Obersee and Untersee (Switzerland) where warmwater species (perches, cyprinids, centrarchids) have become more abundant relative to coldwater forms (whitefish, trout, pike-perch, coregonines) (Larkin and Northcote 1969). Presumably, hypolimnetic oxygen depletion forces coldwater species into shallower areas where their habitat is restricted and they must compete with warmwater fishes.

154. Thus, mixing of eutrophic lakes should shift fish communities toward species characteristic of oligotrophic conditions. Some flaws in the analogy between mixing effects and trophic state should be noted, however. For example, oligotrophic lakes may be poor in littoral habitat, with fewer species of aquatic macrophytes, less dense plant growth, and sparser prey populations than richer lakes. Mixing of a eutrophic lake will probably not decrease the quality of the littoral habitat, so mixed eutrophic lakes should have more warmwater fish species than natural oligotrophic lakes.

155. Aeration of the entire water column under climatic circumstances favorable to coldwater fisheries should therefore produce a diverse fishery. Warmwater species should continue to reside in shallow waters, although some increase in depth distribution

may be observed. Coldwater forms will probably distribute themselves throughout the lake. Based on foregoing arguments, one predicts that the species richness (i.e., number of species) of fishes in artificially mixed eutrophic lakes will be potentially greater than that in either natural eutrophic or natural oligotrophic lakes.

156. Interactions with nutrients. Fishes probably have an important role in regulating the availability of phosphorus in lakes, but our present knowledge of mechanisms is limited (Nakashima and Leggett 1980). After removal of planktivorous fish (roach) from a Swedish lake, Henrikson et al. (1980) observed decreases in total phosphorus, total nitrogen, and limnetic primary production, accompanied by a shift toward larger phytoplankton. Although phosphorus excretion by fishes may be a major source of nutrients for phytoplankton in ponds or experimental enclosures (e.g., Lamarra 1975, Andersson et al. 1978), several investigators have concluded that it is insignificant in lakes relative to nutrient release rates exhibited by zooplankton (Kitchell et al. 1975; Nakashima and Leggett 1980). Kitchell et al. (1975, 1979) proposed that fish may stabilize phytoplankton cycles by excreting a continuous but low supply of phosphorus. They also suggested that winter and postspawning mortality of fish may account for a significant portion of total phosphorus available to plankton in spring. Finally, by removing large prey and shifting the zooplankton community towards smaller species, fish could increase phosphorus turnover rates (Bartell and Kitchell 1978). Some evidence exists for the role of mortality and size-selection predation in regulating phosphorus supplies (i.e., last two hypotheses), but plankton stabilization and direct supply of nutrients by fish excretion appear to be unimportant (Nakashima and Leggett 1980).

Review of Mixing Experiences

157. The following section provides a summary of lake responses to artificial circulation treatments. The first subsection describes methods used in the analysis of lake responses. The second covers the results of mixing experiments in general. The third subsection deals with partial mixing, and the last two subsections discuss aspects of seasonal timing and long-term effects of artificial mixing.

Methods

158. The analysis of lake responses to artificial mixing is based on a qualitative assessment of changes in a total of at least 25 physical, chemical, and biological parameters; these include: temperature differential between surface and bottom water; Secchi depth; dissolved oxygen; nutrients; phytoplankton biomass and taxonomic composition; and the abundances and depth distributions of zooplankton, benthic macroinvertebrates, and fishes. In general, the response categories consisted of: (+) an increase in the parameter value during mixing as compared with pretreatment values; (-) a decrease due to treatment; (0) no change between treatment and pretreatment periods; and ($\pm$, $\overset{+}{0}$, $\overset{-}{0}$, ?) a variable or questionable response. In lakes where mixing experiments were performed for more than one year, individual years were analyzed as separate cases. Seasonal treatments within a year were considered as a single experiment however. In this case, an overall response was assigned to the year.

159. Qualitative responses were used as indicators of treatment effects because in most lakes quantitative data were not available for some parameters. Secondly, results were often given in graphic form only; error in reading quantitative values from the graphs introduces considerable variability into a calculated "mean response." Where quantitative responses were of critical interest, the latter procedure was used and a range of values for the response parameter is given also; in these cases, statistical analysis of results is still based on qualitative patterns.

160. For each response parameter with more than 15 experimental cases, the significance of treatment effects was determined by departure from random expectation of equal number of cases in each of three response categories (+, -, 0). The "variable" and "questionable" categories were omitted from this analysis since there is no reason a priori to expect equal representation of these responses under the null hypothesis. A Chi-square Goodness-of-Fit test was used to detect differences in the observed frequencies of lakes among response categories and the expected uniform frequencies. The analysis was first run on the complete data set including responses from mixing experiments using diffused air as well as those using mechanical pumps. A second test was performed using only the data from diffused-air systems.

161. To determine if differential responses among lakes (or among years within a lake) were related to quantitative characteristics of the mixing systems or morphometry of the lake basin, a stepwise Multiple Discriminant Analysis was applied to 41 diffused-air lakes. For each response parameter analyzed, lakes with the same qualitative response were placed in a single group. In some cases, a group with a limited number of lakes (< 4) was pooled with another group(s) (see below). For each response parameter, discriminant analysis then attempts to separate a given group of lakes (i.e., a response group) from all other groups on the basis of mixing system variables and lake morphometry. As before, individual years were considered as separate experiments, but seasonal results were pooled. When air flow rate or air release depth varied within a single year, the midpoint of the range was used for the Multiple Discriminant Analysis. The statistical analyses were run on a PRIME computer using a package program available through SPSS (Statistical Packages for the Social Sciences).

Experimental systems and response analysis

162. The analysis of lake responses to artificial circulation examines lake and mixing system parameters and relates them to the observed physical, chemical, and biological effects of treatment. All mixing experiences are reviewed in the following sections regardless of the initial management goal (e.g., water quality control, phytoplankton reduction, fisheries enhancement) or the achieved effects on thermal stratification, e.g., prevention of stratification (destratification, thermocline lowering). Specific aspects of partial circulation and the timing of induced mixing are treated later.

Lake characteristics and mixing systems

163. Table 4 provides a summary of basin morphometry and mixing system characteristics for lakes subjected to artificial circulation. The majority of systems have employed diffused air and an unconfined bubble plume to create turbulence. In Cox Hollow Reservoir, Mirror Lake, and Pfaffikersee, diffused air entered the bottom of a vertical tube which enclosed the bubble plume for at least part of its travel distance to the surface. A special surface aerator was operated in Indian Brook Reservoir. Mechanical pumps which produced a flow of water in a confined path from the epilimnion to the hypolimnion or vice versa were used in Boltz Lake in 1965, King George VI Reservoir,

TABLE 4. SELECTED LAKES AND MIXING SYSTEMS

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume x 10^{-6} (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Q_A/V x 10^6	Q_A/A x 10^6	Start Date	Strat.	Dura. (mo)
Cline's Pond Oregon	Malueg et al. 1973	rectangular	4.9	~2.5	4.9	~0.003	0.13	0.028	10.2	21.50	06/30/69	yes	2
Parvin Lake Res. Colorado	Lackey 1972	rectangular	10	4.4	10	0.849	19	2.1	2.5	11.18	11/69	yes	12
Section 4 Lake Michigan	Fast 1971a	circular	19.1	9.8	18.3	0.110	1.1	2.21	20	200	06/16/70	yes	2.8
Boltz Lake Res. Kentucky	Symons et al. 1967, 1970 Robinson et al. 1969	dentritic	18.9	9.4	18.9	3.614	39	3.17	0.88	8.17	08/06/65 06/02/66	yes yes	1.2 1.7[b]
University Lake Res. North Carolina	Weiss and Breedlove 1973	irregular	9.1	3.2	9.1	2.591	80.9	0.40	0.15	0.49	05/19/71 03/27/70		6 ~8
Kezar Lake New Hampshire	N.H.W.S.P.C.C. 1971 Haynes 1973, 1975	subcircular	8.2	2.8	8.2	2.008	73	2.83	1.41	3.88	07/16/68 05/28/69 05/70 05/71	yes yes	2 3.5 3.4 3.4
King George VI Res. United Kingdom	Ridley et al. 1966 Ridley 1970	rectangular	16	14	10- 14	20	142		pump		07/02/65 07/13/66	yes yes	0.2
Indian Brook Res. New York	Riddick 1957	elliptical	8.4	4.1	2.2	0.302	7.3	4.53	15.0	62.06	06/56	yes	6
Prompton Lake Res. Pennsylvania	McCullough 1974	elongate?	10.7	~3.7	10.7	4.193	~112	4.53	1.08	~4.04			
Cox Hollow Res. Wisconsin	Wirth and Dunst 1967 Wirth et al. 1970	lunate	8.8	3.8	8.8	1.480	38.8	2.04- 4.08	1.38- 2.76	5.26- 10.52	07/01/66	yes yes	38.5
Stewart Lake Res. Ohio	Barnes and Griswold 1975 Barnes (pers. comm.)[c]	rectangular	7.5	3.4	7.0	0.090	2.6	0.25	2.83	9.80	07/26/74 07/15/75	yes yes	3[b] 3.5[b]
Wahnbach Res. W. Germany	Bernhardt 1967	elongate	43	19.2	~43	41.618	214	2.01 5.95	0.048 0.143	0.94 2.78	05/26/61 06/13/62 06/11/64	yes	4.5[b] 5 5
Starodworskie Lake Poland	Lossow et al. 1975	elliptical	23		23		7	0.27		3.81	03/14/72	yes	6.2
Queen Elizabeth II Res. United Kingdom	Ridley et al. 1966 Tolland 1977	subcircular	17.5	15.3	17.5	19.6	128		water jet		03/15/65 05/24/66	yes yes	
Lake Roberts Res. New Mexico	R.S. .err Res. Center 1970 McNall 1971	irregular	9.1	~4.4	9.1	1.233	28.3	3.54 2.26	2.87 1.84	12.51 8.00	06/15/69 07/09/69	yes yes	0.2 1.6

(Continued)

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TABLE 4. (continued)

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume $\times 10^{-6}$ (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Aeration Intensity[a] $Q_A/V \times 10^6$	Aeration Intensity[a] $Q_A/A \times 10^6$	Start Date	Strat.	Dura. (mo)
Falmouth Lake Res. Kentucky	Symons et al. 1967, 1970 Robinson et al. 1969	elongate	12.8	6.1	12.8	5.674	91	3.26	0.58	3.58	05/16/66		4[b]
Test Res. II United Kingdom	Knoppert et al. 1970	rectangular	10.7	9.4	10.7	2.405	25.4	2.01	0.84	7.92	04/01/68		5
Ham's Lake Res. Oklahoma	Steichen et al. 1974, 1979 Toetz 1977a, b; 1979b Garton et al. 1978 Wilhm et al. 1979	dentritic	10	2.9	pump 1.2	115	40		Garton pump		07/16/73 06/19/75 06/03/76 04/19/78 05/31/79	yes yes yes yes yes	3.5 3 3 4.8 3
Test Res. I United Kingdom	Knoppert et al. 1970	rectangular	10.7	9.4	10.7	2.097	22.7	2.01	0.96	8.86	06/68		4[b]
Mirror Lake Wisconsin	Smith et al. 1975 Brynildson and Serns 1977	elliptical	13.1	7.6	12.8	0.400	5.3	0.45	1.13	8.55	10/19/72 03/30/73 09/21/73 09/12/74	yes	1 0.8 0.5 1.5
Stewart Hollow Res. Ohio	Irwin et al. 1966	rectangular	7.6	4.6	pump 7.6	0.148	3.2		axial-flow pump		07/20/64 09/01/64	yes yes	0.1 0.04
Cladwell Res. Ohio	Irwin et al. 1966	irregular	6.1	3.0	pump 6.1	0.123	4.0		axial-flow pump		07/29/64	yes	0.07
Pine Res. Ohio	Irwin et al. 1966	lunate	5.2	2.1	pump 5.2	0.121	5.7		axial-flow pump		08/05/64	yes	0.1
Vesuvius Res. Ohio	Irwin et al. 1966	elongate	9.1	3.6	pump 9.1	1.554	42.5		axial-flow pump		09/03/64	yes	0.8[b]
Vaxjosjon Sweden	Bengtsson and Gelin 1975	elliptical	6.5	3.5	6	3.1	87	7.2	2.32	8.28	summer 1969-71 winter 1971		0.2- 0.5 0.5
Corbett Lake British Columbia	Halsey 1968 Halsey and Galbraith 1971	elliptical	19.5	7	19.5	1.689	24.2	4.50	2.66	18.52	10/17/62 10/18/63	yes yes	1.5[b] 1.5[b]
Buchanan Lake Ontario	Brown et al. 1971	elliptical	13	4.9	13	0.42	8.9	0.28	0.67	3.17	07/14/71	yes	2.5
Lake Maarsseveen United Kingdom	Knoppert et al. 1970	irregular	29.9	14	19 29.9	8.018	60.7	2.49	0.31	4.10	07/27/67	yes	1.8[b]

(Continued)

(Sheet 2 of 4)

TABLE 4. (continued)

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume x 10^{-6} (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Aeration Intensity[a] Q_A/V x 10^6	Aeration Intensity[a] Q_A/A x 10^6	Start Date	Strat.	Dura. (mo)
Arbuckle Lake Res. Oklahoma	Toetz 1977a, b; 1979a, b	dendritic	24.7	9.5	6 2	8930	951		Garton pump		07/17/74 06/02/75 [illegible]/01/77 [illegible]4/01/78	yes yes yes yes	1.5 3.5 2.8 6
Casitas Res. California	Barnett 1975	dendritic	82	26.8	39- 55	308	1100	17.84	0.06	1.62	04/70 to 1975		~7/yr
Hyrum Res. Utah	Drury et al. 1975	elliptical	23	11.9	15.2	23.1	190	2.83	0.17	1.49	06/01/73	yes	12
West Lost Lake Michigan	Hooper et al. 1953	circular	12.8	6.2	pump 11.9	0.089	1.4		pump		29/52	yes	0.4
Waco Res. Texas	Biederman and Fulton 1971		23	10.7	23	128	2942	3.11	0.02	0.10	06/10/67	yes	~48[b]
Lake Catherine Illinois	Kothandaraman et al. 1979	elliptical	11.8	5	8.5	3.034	59.5	0.76	0.25	1.27	05/18/78	yes	5.5
El Capitan Res. California	Fast 1968	elongate	62	9.8 9.4	21.3 28.3	17.99 21.05	183.9 222	6.09 6.09	0.34 0.29	3.31 2.74	06/65 02/66	yes yes	3.7 7
Lake Calhoun Minnesota	Shapiro and Pfannkuch 1973		27.4	10.6	23	18.01	170.4	2.83- 3.54	0.16- 0.20	1.66- 2.08	08/04/72	yes	4
Eufaula Res. Oklahoma	Leach et al. 1970	irregular	27	8.3	27	3454	41480	33.98	0.01	0.08	06/67 07/68	yes yes	0.8 1.1
Pfaffikersee Switzerland	Thomas 1966 Ambuhl 1967	elliptical	35	18	28	56.5	325	6	0.11	1.85	4 or 5 1958-63	yes	4-5
Wahiawa Res. Hawaii	Devick 1972	elongate	26	~8	2.7	-1.7	20	2.4	~1.4	12	09/20/71	yes	2
Trasksjon Sweden	Karlgren and Lindgren 1963	elliptical	4	~3.0	4?	0.365	12.1				03/63	yes	0.07
Allatoona Res. Georgia	USAE 1973 Raynes 1975	dendritic	46	9.4	42.7	453	4800	21.6- 27.7 27.7	0.05- 0.06 0.06	0.45- 0.58 0.58	05/09/68 03/15/69	yes yes	4.5 6.5
Lafayette Res. California	Laverty and Nielsen 1970	lunate	24	9.1	18	5.243	53	1.68	0.32	3.17	04/68	yes	9[b]
Hot Hole Pond New Hampshire	N.H.W.S.P.C.C. 1979	elliptical	13.3	5.7	13.3	0.733	12.9	0.59	0.80	4.57	05/04/76	yes	3.6

(Continued)

(Sheet 3 of 4)

TABLE 4. (continued)

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume x 10^{-6} (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Q_A/V x 10^6	Q_A/A x 10^6	Start Date	Strat.	Dura. (mo)
Heart Lake Ontario	Nicholls et al. 1980 Nicholls (pers. comm.)[d]	elliptical	10.4	2.7	10	0.392	14.5	0.23	0.58	1.56	06/25/75	yes	1.2
								0.34	0.88	2.38	07/31/75	no	4.6
								0.34	0.88	2.38	04/07/76	no	4.4
								0.34	0.88	2.38	06/79	yes	3-5
								0.34	0.88	2.38	04/80	no	~3
								0.92	2.34	6.33	07/80	no	3-5
Clear Lake California	Rusk (pers. comm.)[e]	irregular	15	10.2	14	115.93 OAKS	1217 OAKS	17	6.82	1.40	1976	yes	
Kremenchug Res. Inlet Poland	Ryabov et al. 1972 Sirenko et al. 1972		3	~2	2.6	0.002	~0.12	4.38	1750	~3500	07/17/70	yes	0.7[b]
Tarago Res. Australia	Bowles et al. 1979	irregular	23	10.5	14	37.6	360	3.00-9.00	0.08-0.24	0.83-2.50	01/21/76	yes	1.1[b]
								3.00-7.50	0.08-0.20	0.83-2.08	10/05/76	yes	2.5[b]

[a] Q_A = rate of air injection (m^3/min), V = volume (m^3), A = area (m^2).

[b] Intermittent operation of aerator or pump.

[c] Personal communication, M.D. Barnes, October, 1980, Ohio State University, Columbus, Ohio.

[d] Personal communication, K.H. Nicholls, October, 1980, Ontario Ministry of the Environment, Ontario, Canada.

[e] Personal communication, W.F. Rusk, October, 1980, University of California, Berkeley, California.

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four Ohio reservoirs, and West Lost Lake. A propeller-type Garton pump was used in Ham's Lake and Arbuckle Lake. Finally, Queen Elizabeth II Reservoir was circulated by a water-jet system employing river water.

164. The selected lakes represent a variety of basin types, the smallest being a pond at the Kremenchug Reservoir Inlet (Poland) and the largest being Arbuckle Lake (Oklahoma). The deepest point of air release was 55 m, in the deepest water body Casitas Reservoir (California).

165. Lorenzen and Fast (1977) concluded that the best measure of aeration intensity for a diffused-air system was air flow rate divided by lake surface area. They recommended an air flow of 9.2 m^3/min per 10^6 m^2 of lake surface (= 30 SCFM per 10^6 ft^2) to attain good mixing; i.e., near-uniform depth profile of phytoplankton and a temperature differential between surface and bottom of less than 2°C. According to this scaling rule, the majority of mixing systems listed in Table 4 were grossly undersized.

Physical responses

166. The physical and chemical effects of artificial circulation are summarized in Table 5 according to lake and year of mixing. Statistical analysis of the results is given in Tables 6 and 7.

167. Temperature. Artificial circulation resulted in a temperature differential of 3°C or less between surface and bottom waters in 63 percent of all mixing experiments (Table 6) and in 67 percent of diffused air treatments (Table 7). The effect of mixing was significant at the $P < .05$ level. Those lakes with larger temperature differentials (i.e., > 3°C) were sometimes partially mixed by releasing air at a depth less than the maximum depth; e.g., Casitas Reservoir, Lake Calhoun, El Capitan Reservoir (Table 4). More often, partial stratification was the result of inefficient mixing (see below, "Partial mixing"). Artificial circulation usually promotes an increase in he summer heat content of the lake, even when mixing is incomplete (e.g., Toetz et al. 1972; Haynes 1973; Toetz 1977b, 1979a; Kothandaraman et al. 1979). Surface temperatures may decrease slightly relative to control years, whereas deep waters are warmed by as much as 15 - 20°C. In north temperate lakes, circulation during winter reduces water temperatures overall (Drury et al. 1975).

TABLE 5. PHYSICAL AND CHEMICAL RESPONSES TO ARTIFICIAL CIRCULATION[a]

Lake	Year(s)	ΔT (°C) Before	ΔT (°C) After	SD	DO	PO_4	TP	NO_3	NH_4	Fe Mn
Cline's Pond		6	0	+	+	+		0	0	
Parvin Lake Res.		6	<3		+			0		
Section 4 Lake		15	0	-	+					
Boltz Lake Res.	1966	5-10	<2	-	-		-	+	±	-
University Lake Res.			<2	-	+ 0	-	-	+	-	-
Kezar Lake	1968	11	<1	+	+	+	+	±	-	-
	1969	2	<2	-	+	±	+	+	-	-
King George VI Res.	1965	6.5	6		+					
	1966	6.5	4		+					
Indian Brook Res.		9	0		+					-
Prompton Lake Res.			1							
Cox Hollow Res.	1966	17	<3	+	+	-		+	-	-
	1967-69		<3	0	+	-			-	-
Stewart Lake Res.	1974	19	5		+	0		-		
	1975	18	7		+	0		-		
Wahnbach Res.	1961-62	14	6		+ 0					-
	1964		<2		+					-
Starodworskie Lake		15	<2		+	-	-	+	-	
Queen Elizabeth II Res.	1965	6	0		+					
	1966	4	0		-	+				
Lake Roberts Res.	06/69	6	0		+		-			
	07/69	4.6	0		-		+			
Falmouth Lake Res.			0-8	-	±		-	$\bar{0}$	-	-
Test Res. II			0	-	+		0	-	-	
Ham's Lake Res.	1973	13.5	<1		+					
	1975	10	<2	+	+	+		-	-	-
	1976	9-10	<2	-	+	+		+	0	
	1978	9-10	<2	-	+	0		0	0	
	1979	(Continued)			+					-

(Sheet 1 of 3)

TABLE 5. (continued)

Lake	Year(s)	ΔT (°C) Before	After	SD	DO	PO_4	TP	NO_3	NH_4	Fe Mn
Test Res. I			0	0	+		0	-	-	
Mirror Lake	1972	13	0		+	-	+			
	1973		0		+	0	-			
Stewart Hollow Res.		22	13		0					
		15	<2		0					
Cladwell Res.		20	7		+					
Pine Res.		13	3		-					
Vesuvius Res.		16	2		0					
Vaxjosjon			0		+		+			
Corbett Lake		2-4	0		+					
Buchanan Lake			0	-	+		-		-	-
Lake Maarsseveen		8	0							
Arbuckle Lake Res.	1975	11	9	0	0	0		0	0	0
	1977	9	13	0	+	+		+	-	
	1978		10	0	+			0	-	0
Casitas Res.			b	+ 0						-
Hyrum Res.		6	2-4	-	+	0	0	-	-	
West Lost Lake		13	9	-	+		+			
Waco Res.		17	~6		+					
Lake Catherine		2	0-14	0	+	0	0	0	0	0
El Capitan Res.	1965	~9	<3	-	+					-
	1966	~6	<3	-	+					-
Lake Calhoun		16	9[b]	-	+					
Eufaula Res.		10	7		0					
Pfaffikersee			>3		+			+	-	
Wahiawa Res.		(Continued)	b							

(Sheet 2 of 3)

TABLE 5. (continued)

Lake	Year(s)	ΔT (°C) Before	ΔT (°C) After	SD	DO	PO_4	TP	NO_3	NH_4	Fe Mn
Trasksjon		7	0		0					
Allatoona Res.	1968	9-13	4-6		+	0	0	-	+	-
	1969	3-13	3-6		+	0	0	-	+	-
Lafayette Res.		9	0-7		+					
Hot Hole Pond		8-20	<3		+	-	-	-	-	-
Heart Lake	1975	10-14	<2		+					
	1976	0	0-4		±	+	+	+	+	
Clear Lake	1976	6	0	0	+	0?			-	0
Kremenchug Res. Inlet			0	+	0			+	0	
Tarago Res.	1976	12	7-10		+		0			-
	1977	7	0-7		+		0			-

[a] Response parameters: ΔT = temperature differential between surface and bottom water
SD = Secchi depth
DO = dissolved oxygen
PO_4 = phosphate
TP = total phosphorus
NO_3 = nitrate
NH_4 = ammonium
Fe = iron
Mn = manganese

Direction of change in average value for whole water column:
+ = increase
- = decrease
0 = no significant change

See Table 4 for references.

[b] Mixed to air release depth only.

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TABLE 6. SUMMARY OF LAKE RESPONSES TO ARTIFICIAL CIRCULATION, MECHANICAL AND DIFFUSED-AIR SYSTEMS

PARAMETER	N		LAKE RESPONSES +	-	0	?	χ^2
ΔT After[a]	62	No.	23	39	-	-	4.13*
		%	37	63	-	-	
Secchi Depth	26	No.	5	13	5	3	5.57
		%	19	50	19	12	
Dissolved Oxygen	57	No.	45	2	5	5	66.5***
		%	79	4	9	9	
Phosphate	24	No.	7	6	9	2	0.64
		%	29	25	38	8	
Total P	22	No.	6	7	8	1	0.29
		%	27	32	36	5	
Nitrate	27	No.	10	9	6	2	1.04
		%	37	33	22	7	
Ammonium	27	No.	3	17	6	1	12.5**
		%	11	63	22	4	
Iron/Manganese	26	No.	0	22	4	0	31.7***
		%	0	85	15	0	
Epilimnetic pH	31	No.	1	15	12	3	11.6**
		%	3	48	39	10	
Algal Density	48	No.	7	17	17	7	4.88
		%	15	35	35	15	
Biomass/Chlorophyll	32	No.	6	7	12	7	2.48
		%	19	22	38	22	
Green Algae	23	No.	7	7	9	0	0.35
		%	30	30	39	0	
Bl.-Gr. Algae	36	No.	8	18	8	2	5.88
		%	22	50	22	6	
Ratio Gr:Bl-Gr	34	No.	12	5	12	5	3.38
		%	35	15	35	15	

[a] Temperature differential between surface and bottom water during artificial mixing. + means $\Delta T>3°C$; - means $\Delta T \leq 3°C$.

* P<.05 Goodness-of-fit test to uniform frequency distribution for +, -, 0 responses only.
** P<.01
*** P<.001

TABLE 7. SUMMARY OF LAKE RESPONSES TO ARTIFICIAL CIRCULATION, DIFFUSED-AIR SYSTEMS ONLY

PARAMETER	N		LAKE RESPONSES				X^2
			+	-	0	?	
ΔT After[a]	45	No.	15	30	-	-	5.00*
		%	33	67	-	-	
Secchi Depth	19	No.	4	10	2	3	6.50*
		%	21	53	10	16	
Dissolved Oxygen	41	No.	33	1	2	5	55.2***
		%	80	2	5	12	
Phosphate	17	No.	3	5	7	2	1.60
		%	18	29	41	12	
Total P	20	No.	5	6	8	1	0.74
		%	25	30	40	5	
Nitrate	20	No.	7	8	3	2	2.33
		%	35	40	15	20	
Ammonium	20	No.	3	13	3	1	10.5**
		%	15	65	15	5	
Iron/Manganese	22	No.	0	20	2	0	33.1***
		%	0	91	9	0	
Epilimnetic pH	21	No.	1	9	8	3	6.33*
		%	5	43	4	14	
Algal Density	33	No.	6	14	8	5	3.71
		%	18	42	24	15	
Biomass/Chlorophyll	23	No.	5	6	6	6	0.12
		%	22	27	27	27	
Green Algae	18	No.	7	4	7	0	1.00
		%	39	22	39	0	
Bl.-Gr. Algae	25	No.	5	13	5	2	5.57
		%	20	52	20	8	
Ratio Gr:Bl-Gr	21	No.	11	3	6	1	4.90
		%	52	14	29	5	

[a] Temperature differential between surface and bottom water during artificial mixing. + means $\Delta T > 3°C$; - means $\Delta T \leq 3°C$.

* $P < .05$ Goodness-of-fit test to uniform frequency distribution for +, -, 0 responses only.
** $P < .01$
*** $P < .001$

168. Schematic representations of thermal stratification and mixing patterns are given in Figure 7. Examples of patterns observed during artificial destratification experiments are given below:

PATTERN	EXAMPLES
• Complete mixing	Cline's Pond, Kezar Lake
• Thermocline lowering	Lake Calhoun, El Capitan Reservoir, Wahiawa Reservoir
• Surface microstratification	Hyrum Reservoir, El Capitan Reservoir
• Localized destratification	Clear Lake Prompton Lake Reservoir
• Localized thermocline lowering	Arbuckle Lake, Eufaula Reservoir

169. Secchi depth. Artificial mixing has varied effects on water transparency. Although 50 percent of all case studies showed a decrease in Secchi disc after mixing, the treatment effects were not statistically different from a random expectation of equal number of cases in each response category (i.e., +, -, 0; Table 6). Adequate mixing may increase transparency immediately by distributing a surface bloom of blue-green algae throughout a greater volume (Haynes 1973). In the long term, mixing may enhance transparency by reducing algal biomass (Malueg et al. 1973; Lorenzen and Mitchell 1975). In contrast, resuspension of bottom sediments nullified the effects of a slight decline in phytoplankton at Section Four Lake, and the Secchi depth declined after mixing (Fast 1971a). Incomplete mixing may reduce water clarity by fostering algal blooms; e.g., West Lost Lake and Hyrum Reservoir (Hooper et al. 1953; Drury et al. 1975). In general, a rise in total seston during mixing correlates with a decrease in transparency (Fast 1971a, Drury et al. 1975; Garton 1978; Garton et al. 1978).

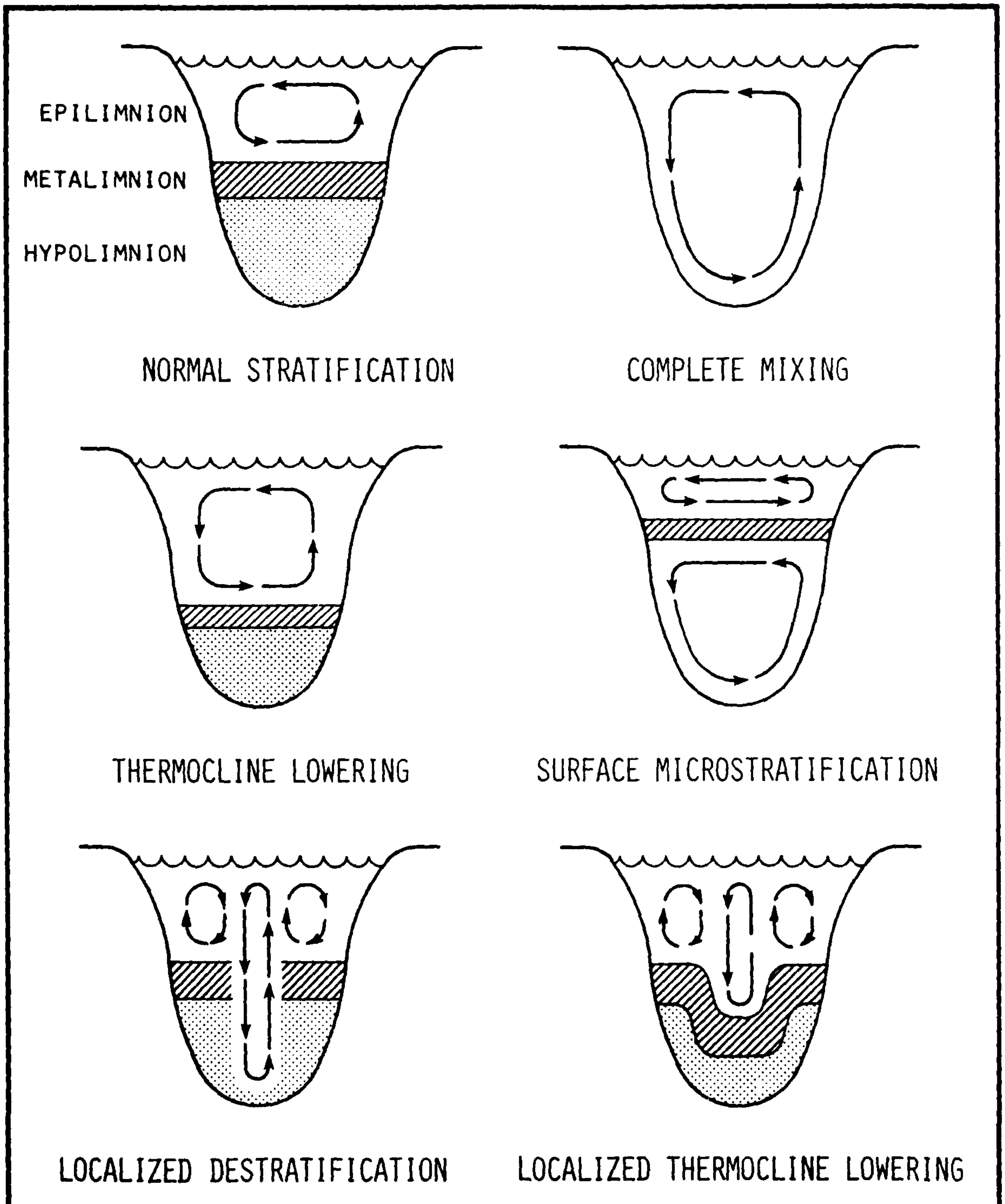

Figure 7. Patterns of lake stratification and mixing.

Chemical responses

170. Dissolved oxygen. The vast majority of mixing experiments have been successful in raising the average dissolved oxygen (DO) concentration in the water column (Tables 6 and 7). Immediately after artificial destratification, the oxygen concentration in bottom waters increases (e.g., Hooper et al. 1953; Lackey 1972; Haynes 1973, 1975). DO in the former epilimnion shows a corresponding decline due to a reduction in photosynthesis (Haynes 1973) combined with higher BOD related to previous conditions in the hypolimnion. Eventually, an adequate mixing system can satisfy this BOD and raise average DO.

171. Nutrients. Average concentrations of phosphate, total phosphorus, and nitrate showed varied responses to artificial mixing (Tables 6 and 7). In practice, approximately equal numbers of case studies were found in each main response category (+, -, 0). On the other hand, artificial mixing clearly reduced the average concentration of ammonium.

172. The impact of destratification on dissolved nutrient levels is largely unpredictable due to the complex interactions among inorganic, detrital and biotic compartments (Toetz et al. 1972; Fast 1975). For example, mixing may elevate total phosphorus by resuspending detritus-rich sediments or by maintaining dead algal cells in suspension (Hooper et al. 1953; Wirth and Dunst 1967; Fast 1971a; Haynes 1973). Decomposition of detritus in the water column releases inorganic forms of phosphorus. In Boltz Lake and Falmouth Lake, mixing increased organic nitrogen levels, possibly by breakage or lysis of algal cells (Robinson et al. 1969). Excretion of phosphorus by zooplankton is an important recycling mechanism within the mixed layer (Devol 1979; Lehman 1980b). Finally, total phosphate may decline due to algal uptake (e.g., June experiment at Lake Roberts); or it may increase after the collapse of a phytoplankton bloom (e.g., July experiment at Lake Roberts) (R.S. Kerr Research Center 1970; McNall 1971).

173. In general, it appears that mechanical mixing systems in small lakes produce effects on nutrient levels similar to those induced by release of diffused air (Table 5). Although the data are limited, it is clear that propeller pumps located at the surface are incapable of producing extensive changes in nutrient levels of large reservoirs, e.g., Arbuckle Lake (Toetz 1977a, b; 1979a, b).

174. Iron/manganese. Artificial circulation experiments have been most successful at reducing average lake concentrations of iron and manganese (Tables 6 and 7). Undoubtedly, this response is caused by elevation of redox potential and precipitation of oxidized forms (Bernhardt 1974; Chen et al. 1979).

175. Nitrogen gas supersaturation. Data on N_2 supersaturation and its effects on fish populations during artificial mixing are limited; sample size is inadequate for statistical analysis. At lower depths, air injection clearly increases N_2 concentrations above saturation relative to standard surface conditions (Fast 1979a, b; Smith 1980).

176. At Casitas Reservoir, Fast (1979a, b) found that N_2 levels in the zone of induced mixing (15 - 45 m) were at 125 percent saturation relative to surface pressures after 80 days of aeration in 1977. The waters below 46 m were 140 percent saturated with N_2 relative to the surface. Assuming aeration did not greatly influence N_2 content below the depth of air release, such high N_2 concentrations may be normal for this reservoir.

177. Smith (1980) briefly described the results of field studies undertaken during the summer of 1979 by the U.S. Army Engineer Waterways Experiment Station to quantify nitrogen supersaturation produced by artificial aeration. The diffused-air systems were associated with nitrogen supersaturation (Table 8), but the mechanism of causation is unclear. Smith (1980) suggested that increased temperatures accompanying destratification could contribute substantially to the degree of supersaturation. In all reservoirs, dissolved nitrogen concentrations were less than the theoretical limits based on temperature and depth. In the smaller reservoirs, N_2 concentrations dropped with time over the stratification cycle, but percent saturation increased.

178. As far as is known, N_2 supersaturation during aeration has not caused any adverse impacts on fish populations in reservoirs. Some fish species can detect and avoid air-supersaturated water (Chamberlain et al. 1980; Stevens et al. 1980). Smith (1980) and others have cautioned against the release of N_2 supersaturated waters to downstream areas, however. At levels of 115 to 135 percent saturation typical of air injection experiments (Table 8), downstream release could induce substantial fish mortality.

TABLE 8. PEAK NITROGEN SUPERSATURATION PRODUCED BY COMPRESSED AIR INJECTION[a]

Lake	Maximum Reservoir Depth (m)	Peak Nitrogen Saturation
Casitas	65	135
El Capitan	42	115
Henshaw	9	104
Mathews	52	111
Morena	25	122
Murray	18	112
Perris	24	112
Puddingstone	18	112
Skinner	23	109
Vail	30	122
Wihlford	19	111

[a] Taken from Smith (1980).

Biological responses

179. Phytoplankton. Phytoplankton responses to artificial circulation are summarized in Tables 6, 7, and 9. For each algal response parameter, Chi-square analysis indicates no significant deviation from an equal number of cases in each response category. Note that the data for areal biomass and average chlorophyll concentration were pooled for the analysis because of limited sample size for each parameter. Overall, there is a tendency for artificial mixing to cause a decline in blue-green algae and elevate the abundance ratio of greens to blue-greens. If a change in algal density follows artificial circulation, decreasing abundance seems more likely than an increase in population levels. However, none of these trends is statistically significant (Tables 6 and 7).

180. When artificial circulation is effective at increasing the depth of mixing, the depth distribution of phytoplankton does expand (Fast 1971a; Haynes 1973), except in shallow ponds where algae were distributed throughout the water column beforehand (Malueg et al. 1973; Ryabov et al. 1972). Presumably, a large mixing depth results in algae spending considerable time in dimly lit zones, perhaps beyond the critical depth in deep lakes (Talling 1971). This probably explains the drop in total primary production that occurs in some mixing experiments; e.g., Kezar Lake (Haynes 1973) and Vaxjosjon (Bengtsson and Gelin 1975). In Lake Vaxjosjon, average primary production (gC m^{-2} day^{-1}) during summer 1970 decreased by about 30 - 40 percent relative to the control year (Bengtsson and Gelin 1975). On the other hand, total primary productivity and productivity per cell during aeration of Section Four Lake were up to three times higher than values during the control year (Fast 1971a). At this oligotrophic lake, nutrients rather than light levels may have been limiting algal growth. Even though aeration circulated phytoplankton throughout the lake, it also resuspended bottom detritus, thereby recycling internal nutrients.

181. Artificial circulation appeared to cause little change in cell concentrations in lakes where populations were low initially (Knoppert et al. 1970; Biederman and Fulton 1971; Toetz 1977a, b, 1979a, b; Kothandaraman et al. 1979; but see Fast 1971a). Assuming most of these lakes are oligotrophic and therefore nutrient limitation prevails, one expects that any given change in mixed depth will

TABLE 9. RESPONSES OF PHYTOPLANKTON TO ARTIFICIAL CIRCULATION[a]

Lake	Reference	Algal Density[b]	Algal Standing Biomass[c]	Mean Chlorophyll-a Concentration	Green Algae	Blue-Green Algae	Ratio Gr:Bl-Gr
Cline's Pond	Malueg et al. 1973	-		-	0	-	+
Parvin Lake	Lackey 1973a	-			-	0[d]	0
Section 4 Lake	Fast 1971a	-[e]	-		-		
	Fast et al. 1973						
Boltz Lake	Symons et al. 1967, 1970	1965 -	-		-	0	+
	Robinson et al. 1969	1966 -	-		-	-	+
University Lake	Weiss and Breedlove 1973	-		0	+	-	+
Kezar Lake	Turner et al. 1972	1968 -	-	0	+	-	+
	Haynes 1973, 1975	1969 -	-		+	-	+
	N.H.W.S.P.C.C. 1971	1970 -	-			-	+
	Lorenzen and Mitchell 1975						
King George VI	Ridley et al. 1966	-			-	+	-
Indian Brook[f]	Riddick 1957	-					
Prompton Lake[f]	McCullough 1974	-					
Cox Hollow[f]	Wirth and Dunst 1967	1966 -					
	Wirth et al. 1970	1967-69 0					
Stewart Lake	Barnes and Griswold 1975	1974 -	-	-	0	-	+
	Barnes 1977; pers. comm.[1]	1975	0	0			
Wahnbach Reservoir	Bernhardt 1967	1964				-	
Starodworskie Lake[e]	Lossow et al. 1975				-	+	-
Queen Elizabeth II	Ridley et al. 1966	1965 0					
		1966 -					
Lake Roberts	McNall 1971	±				±	
	R.S. Kerr Res. Cen. 1970						
Falmouth Lake	Symons et al. 1967, 1970	+			+	-	+
	Robinson et al. 1969						
Test Res. II	Knoppert et al. 1970	+	+		0	+	0

(Continued)

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TABLE 9. (continued)

Lake	Reference	Algal Density[b]	Algal Standing Biomass[c]	Mean Chlorophyll-a Concentration	Green Algae	Blue-Green Algae	Ratio Gr:Bl-Gr
Ham's Lake[e]	Steichen et al. 1974 Toetz 1977a,b, 1979b Garton 1978	1973 0? 1975 0? 1976		+? 0 0	0 0	0 0	0 0
Test Res. I	Knoppert et al. 1970	0?	0+			0+	0-
Mirror Lake	Smith et al. 1975 Knauer 1975	1972 0[g] 1973 0[g]	0[g] 0[g]			0[g] 0[g]	
Stewart Hollow Lake	Irwin et al. 1966	0				-	+?
Cladwell Lake	Irwin et al. 1966	0				-	+?
Pine Lake	Irwin et al. 1966	0				-	+?
Vesuvius Lake	Irwin et al. 1966	0				-	+?
Buchanan Lake	Brown et al. 1971	+	+	+	+	-	+
Lake Maarsseveen[f]	Knoppert et al. 1970	0			0		
Arbuckle Lake	Toetz 1977a, 1979a,b	1974 0 1975 0 1977 0 1978 0		0 0 0 0			0 0 0 0
Casitas Res.[f]	Barnett 1975	-				-	
Hyrum Res.	Drury et al. 1975	+	+	+	-	+	-
West Lost Lake	Hooper et al. 1953	+	+			+	
Waco Res.[f]	Biederman and Fulton 1971	0			0		
Lake Catherine	Kothandaraman et al. 1979	0					0
El Capitan[e]	Fast 1973a	1965 +? 1966 +?					0 0
Lake Calhoun	Shapiro and Pfannkuch 1973		+	+	0	+	-
Pfaffikersee	Thomas 1966	+				+	

(Continued)

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TABLE 9. (continued)

Lake	Reference	Algal Density[b]	Algal Standing Biomass[c]	Mean Chlorophyll-a Concentration	Green Algae	Blue-Green Algae	Ratio Gr:Bl-Gr
Allatoona Res.	USAE 1973 Raynes 1975	1968 0[h] 1969 0[h]	0[h] 0[h]				
Hot Hole Pond[f]	N.H.W.S.P.C.C. 1979	+	+	+		+	-
Heart Lake	Nicholls et al. 1980 Strus 1976 Nicholls (pers. comm.)[j]	1975 1976	0? - +		0 +	0 -	0 +
Clear Lake	Rusk (pers. comm.)[k]	0				0	
Kremenchug Res.	Ryabov et al. 1972 Sirenko et al. 1972	-			+	-	+
U.K. Reservoir[f]	Ridley 1970					-	
Tarago Res.	Bowles et al. 1979	1976 1976-77		-? +?			

[a] + = increase, - = decrease, 0 = no significant change.
[b] Cells or colonies per liter; weighted mean for water column unless noted.
[c] Weight per square meter of lake surface.
[d] Increase observed, but control year was unusual.
[e] Samples were taken near lake surface.
[f] Qualitative information only.
[g] Increase observed, but it was correlated with large input of allochthonous nutrients.
[h] Decreases relative to control year observed at mixed and unmixed stations.
[i] Personal communication, M.D. Barnes, October, 1980, Ohio State University, Columbus, Ohio.
[j] Personal communication, K.H. Nicholls, October, 1980, Ontario Ministry of the Environment, Ontario, Canada.
[k] Personal communication, W.F. Rusk, October, 1980, University of California, Berkeley, California.

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produce small displacements of standing crop compared with potential shifts in richer lakes (discussed earlier in "Phytoplankton: production, concentration, and biomass; Peak biomass vs. mixed depth").

182. Although the effect of mixing on the relative abundance of algal types was not statistically significant, several investigators have observed a dramatic shift from a community dominated by blue-green species to one composed mainly of green algae (e.g., Malueg et al. 1973; Symons et al. 1967, 1970; Sirenko et al. 1972; Weiss and Breedlove 1973; Nicholls et al. 1980). In a few experiments, increases in the blue-green *Aphanizomenon flos-aquae* preceded the succession to green algal species (e.g., Knoppert et al. 1970; Lackey 1973a; Haynes 1975). Hence, Haynes (1975) concluded that artificial circulation can promote large populations of blue-green algae. Continuous mixing during the summer of 1969 at Kezar Lake prevented a late summer bloom of *A. flos-aquae* however (Haynes 1975). The timing of mixing in relation to the peak of an algal bloom and the degree of surface microstratification largely determine the impact of mixing on blue-green populations (see sections below, "Partial mixing" and "Importance of timing").

183. A series of well-controlled experiments in water column enclosures clearly demonstrated that aeration/circulation can shift dominance in the algal community from blue-greens to greens (Shapiro et al. 1975, 1977; Forsberg and Shapiro 1980a, b). In general, a decrease in pH below 7.5 following mixing leads to a predictable shift in relative abundance of algal types (Shapiro et al. 1975). Slow mixing within the enclosures increased the total phosphorus content of surface waters, but failed to lower pH (Forsberg and Shapiro 1980b). In fact, pH generally increased while the blue-green algae *Anabaena circulinus* and *Microcystis aeruginosa* became more abundant in response to higher phosphorus levels. With faster mixing rates, complete destratification occurred and nutrient levels (TP and CO_2) rose at the surface as hypolimnetic waters were mixed upwards. As long as hypolimnetic CO_2 was initially high, pH dropped sifficiently after mixing to produce an increase in the relative abundance of green algae (e.g., *Sphaerocystis schroederi*, *Ankistrodesmus falcatus*, *Scenedesmus* spp.) and diatoms (e.g., *Nitzchia* spp., *Synedra* spp., *Melosira* spp.) (Forsberg and Shapiro 1980b).

184. Mechanisms underlying the shift in community composition are not well understood; several possibilities, including cyanophage activation and changes in competitive advantage, were discussed previously. Shapiro's (1973) hypothesis that community succession is somehow related to a decline in pH is supported by the results of artificial circulation. A shift from blue-greens to greens during whole lake mixing experiments is usually associated with a substantial decline in pH to a final pH value less than 7.5 (Table 10). Experiments which failed to produce a shift toward greens or even stimulated growth of blue-green algae generally showed insignificant change in pH (e.g., Lake Calhoun, Parvin Lake, El Capitan Reservoir); or pH less than 7.5 before mixing (e.g., Arbuckle Lake, Hot Hole Pond).

185. Although a temporary rise in pH followed the 1969 mixing of Kezar Lake (Table 10), after 20 days of aeration pH dropped from 9.0 to 7.1. At that time, a shift in species relative abundance occurred, changing from essentially a monoculture of the blue-green species _Aphanizomenon flos-aquae_ to a mixture of green algae, e.g., _Ulothrix subconstricta_, _Scenedesmus_ spp., _Ankistrodesmus_ spp. (New Hampshire Water Supply and Pollution Control Commission (N.H.W.S.P.C.C.) 1971; Haynes 1975). In four Ohio lakes, artificial destratification maintained low pH in the upper waters and prevented the usual fall bloom of blue-greens (Irwin et al. 1966).

186. Although mixing caused a temporary decrease of epilimnetic pH in Ham's Lake during 1973 and Starodworski Lake, pH values remained above 7.3, failing to enhance growth of green algae. In Hyrum Reservoir, pH of the surface waters rose sharply to 9.2 during aeration due to a bloom of _Aphanizomenon_ (Drury et al. 1975). Partial mixing in Arbuckle Lake, El Capitan Reservoir, and Lake Catherine caused little change in pH and no apparent shift in relative abundance of greens and blue-greens.

187. Extensive data on changes in phytoplankton species composition during artificial circulation is available in Robinson et al. (1969), Weiss and Breedlove (1973), Lackey (1973a), Haynes (1973, 1975), and Nicholls et al. (1980). It is difficult to generalize about treatment effects on individual species because of limited sample size and alternative responses related to site-specific conditions. Nevertheless, the positive response of some diatom

TABLE 10. EPILIMNETIC pH CHANGES ASSOCIATED WITH ARTIFICIAL CIRCULATION

Lake	Reference	Direction of Change	Before	After
Group I[a]				
Cline's Pond	Malueg et al. 1973	-	6.2-9.6[c]	6.4-7.2
University Lake Res.	Weiss and Breedlove 1973	-	7.6[d]	7.3,7.0
Kezar Lake	N.H.W.S.P.C.C. 1971 Haynes 1973	1968 -	9.4	6.7
	N.H.W.S.P.C.C. 1971 Haynes 1975	1969 +	6.6	9
Stewart Lake Res.	Barnes 1977	1974 - 1975 0	7.5(7.1-7.8) 6.5(6.2-6.7)	7.1(7.0-7.4) 6.5(6.3-6.8)
Stewart Hollow Res.	Irwin et al. 1966 Irwin et al. 1966	- -	6.8 6.8	5.5 6.5
Cladwell Res.	Irwin et al. 1966	0	7.3	7.0-7.5
Pine Res.	Irwin et al. 1966	0	6.9-7.2	6.7-7.1
Vesuvius Res.	Irwin et al. 1966	-	6.8-7.3	6.8-7.0
Buchanan Lake	Brown et al. 1971	-	7.1	6.7
Heart Lake	Nicholls (pers. commun.)[e]	1975 - 1976 -		
Kremenchug Res. Inlet	Ryabov et al. 1972 Sirenko et al. 1972	-	9.0-10.0	8.1(7.5-9.0)
Group II[b]				
Parvin Lake Res.	Lackey 1972	0	6.6-7.2[d]	6.7-7.2
Starodworskie Lake	Lossow et al. 1975	-	9.0-9.4[d]	7.3-8.6
Test Res. II	Knoppert et al. 1970	0?	?	>9
Ham's Lake Res.	Steichen et al. 1974, 1979 Toetz 1977b	1973 - 1975 0	~8.5(7.4-9.0) >8	~8.0(7.5-8.7) >8
Test Res. I	Knoppert et al. 1970	0?	?	>9
Arbuckle Lake Res.	Toetz 1977b Toetz 1979a,b	1975 - 1977 0	7.71[d] ~7.5[d]	7.39 ~7.5
Hyrum Res.	Drury et al. 1975	±	7.8-8.9[d]	7.2-9.2
Lake Catherine	Kothandaraman et al. 1979	0	>8[d]	>8
El Capitan Res.	Fast 1968	1965 0 1966 0	7.5-8.6[d] 7.3-8.6[d]	7.7-8.3 7.7-8.4
Lake Calhoun	Shapiro and Pfannkuch 1973	0	8.0-8.5[d]	8.0-8.5
Hot Hole Pond	N.H.W.S.P.C.C. 1979	-	6.5(6.1-7.3)[d]	6.2(5.7-7.0)
Tarago Res.	Bowles et al. 1979	1976 0 1976-77 0	7.0-8.0 7.0-7.4	7.0-7.8 7.0-7.4

[a] Group I = Lakes in which the ratio of green algae to blue-green algae increased after treatment.

[b] Group II = Lakes in which the ratio of green algae to blue-green algae decreased or stayed the same after treatment.

[c] Control section.

[d] Control year, summer values.

[e] Personal communication, M.D. Barnes, October, 1980, Ohio State University, Columbus, Ohio.

species to mixing is clear. Artificial circulation enhances the abundance of Melosira ambigua and M. islandica (Haynes 1975), M. italica subsp. subartica (Lund 1971), and M. granulata (Knoppert et al. 1970; Lackey 1973a). Recall that Melosira spp. have enormous sinking rates in the absence of turbulence (see Table 2). By rapidly mixing water above the thermocline in experimental enclosures, Forsberg and Shapiro (1980b) have separated the effects of turbulence and mixed depth on diatom growth. The population growth rates of diatoms (Nitzchia spp., Synedra spp., Melosira spp.) increased greatly relative to those of green and blue-green species as the level of turbulence was elevated. Thus, the hypothesis that mixing favors algae with high sinking velocities (cf. Bella 1970; Lackey 1973a) is generally substantiated.

188. Among the blue-green algae, Anabaena spp. appear to be particularly sensitive to disturbance by artificial mixing (Ridley 1970; Knoppert et al. 1970; Malueg et al. 1973; Steichen et al. 1974; Barnett 1975). Metalimnetic populations of Oscillatoria, e.g., O. rubescens in Wahnbach Reservoir (Bernhardt 1967) and O. tenuis in University Lake (Weiss and Breedlove 1973) were also decimated by artificial circulation.

189. Zooplankton. Artificial circulation generally leads to an increase in zooplankton abundance and expansion of their vertical distribution (Table 11). Exceptions to this trend can be explained on the basis of inadequate sampling design (Eufaula Reservoir), incomplete mixing (Hyrum Reservoir, Arbuckle Lake), or lack of control data (Ham's Lake, Arbuckle Lake).

190. A predictable pattern of habitat expansion followed artificial mixing at most locations, including El Capitan Reservoir, Mirror Lake, Lake Calhoun, Buchanan Lake, and Heart Lake. For example, the zooplankton were restricted to the upper 10 m of El Capitan Reservoir before aeration; but after 17 days of mixing, 85 percent of the community was found below 10 m (Fast 1971b). Oxygenation of bottom waters establishes a refuge for large zooplankters, which are normally susceptible to visual predation in the surface layer. Although most authors reported substantial changes in the depth distributions of Daphnia and other cladocerans, Lackey (1973b) found little change in habitat occupied by Cladocera and rotifers. However, he did note that Diaptomus occurred in deeper

TABLE 11. RESPONSES OF ZOOPLANKTON TO ARTIFICIAL CIRCULATION[a]

Lake	Reference	Abundance[b]	Depth Distribution	Ratio Copepods: Cladocerans
Parvin Lake	Lackey 1973b	-	+	+
Indian Brook Res.	Riddick 1957	+	+	
Stewart Lake	Barnes and Griswold 1975 Barnes 1977	1974 - 1975 +	0 +	
Starodworski Lake[c]	Lossow et al. 1975	+	0	
Lake Roberts	McNall 1971	+		
Ham's Lake[c]	McClintock 1976	0	0	0
Mirror Lake	Brynildson and Serns 1977	1973 + 1974 +	+ +	+ -
Buchanan Lake	Brown et al. 1971	+	+	
Arbuckle Lake[c,e]	McClintock 1976	0	0	0
Hyrum Res.[d,e]	Drury et al. 1975	0	0	0
El Capitan Res.	Fast 1971b	+	+	
Lake Calhoun[e]	Shapiro and Pfannkuch 1973	+	+	-
Eufaula Res.[d,e]	Bowles 1972	0	0	0
Wahiawa Res.	Devick 1972	+		
Heart Lake	Strus 1976	+	+	

[a] + = increase, - = decrease, 0 = no significant change.

[b] Weighted mean density or standing stock.

[c] Zooplankton distributed to bottom before mix.

[d] Inadequate sampling design or lost samples.

[e] Incomplete mix.

waters during the treatment year. Even in lakes where some zooplankton are normally found in the hypolimnion, destratification shifts the vertical distribution profile toward the bottom (e.g., Ham's Lake, Heart Lake, Starodworski Lake). During the 1975 experiment at Stewart Lake, Barnes (1977) observed a slight expansion of vertical distribution for cladocerans, but not for copepods and rotifers. He attributes the minimal effects of aeration on zooplankton distributions to a positive phototrophic response of organisms under conditions of rapid light extinction with depth.

191. Brynildson and Serns (1977) documented a four-fold increase in *Daphnia* spp. after mixing of Mirror Lake in September 1974. Earlier experiments produced shifts in community composition toward larger *Daphnia* species without changes in total daphnid biomass. The invasion of large-bodied *Daphnia* along with subsequent population growth and occupation of lower waters has been observed repeatedly in artificial circulation experiments; e.g., *D. pulicaria* in Mirror Lake (September 1973 experiment only; Brynildson and Serns 1977), *D. hyalina* in Starodworski Lake (Lossow et al. 1975), *D. pulex* in Heart Lake (Strus 1976), and large *Daphnia* spp. in Lake Calhoun (Shapiro and Pfannkuch 1973; Shapiro et al. 1975). An exception to this trend is Parvin Lake where *D. schodleri* and Cladocera in general were less abundant during aeration; however, the control year was unusual due to absence of the late summer bloom of *Aphanizomenon flos-aquae* (cf. Lackey 1973a). *Daphnia* were also less abundant during the 1976 treatment year at Hot Hole Pond relative to a control period in the previous year (N.H.W.S.P.C.C. 1979). Because little information is available on planktonic food resources and fish predation at that lake, the reason for the *Daphnia* decline remains unclear.

192. Smaller-bodied cladocerans (e.g., *Bosmina*, *Diaphanasoma*) and calanoid copepods (e.g., *Diaptomus*) may exhibit population growth following artificial circulation. The magnitude of increase is rarely as dramatic as that observed for *Daphnia* spp. (e.g., Shapiro et al. 1975; Brynildson and Serns 1977).

193. At Stewart Lake, Barnes (1977) found that the mean abundances of cladocerans and copepods during the 1975 treatment period increased significantly compared to the control year (1973). Barnes (1977) attributed the decrease in total zooplankton abundance

during the 1974 experiment to lack of sufficient food and H_2S toxicity. H_2S gas was mixed into the upper waters and vented to the atmosphere during 1974 but not during 1975.

194. Conflicting evidence regarding the effects of mixing on rotifer populations precludes generalizations at present. Total rotifer abundance exhibited little or no change during aeration of Stewart Lake compared to a previous control year (Barnes 1977). In contrast, Lackey (1973a) observed a decline of rotifers during winter and an increase during summer of the treatment year at Parvin Lake relative to the control period. At Starodworski Lake, rotifers were less abundant during late summer and autumn of the treatment year relative to a similar season during the control year (Lossow et al. 1975).

195. Little information is available to evaluate changes in the abundance of individual zooplankton species following artificial mixing. Apart from the invasion of *Daphnia* spp., overall shifts in species composition and relative abundance apparently caused by circulation have not been well documented. No apparent trend in the ratio of copepods to cladocerans is associated with artificial mixing (Table 11). Lossow et al. (1975) noted a shift in dominance relations of *Bosmina* species, with *B. coregoni* increasing over *B. longirostris*, but competitive exclusion did not occur. In terms of relative abundance, rotifers tended to exhibit less dominance over crustaceans during circulation of Stewart Lake than during the control year (Barnes 1977).

196. Strus (1976) described extensive changes in zooplankton assemblages following aeration of Heart Lake. *Daphnia pulex* invaded the lake and replaced the smaller *D. rosea*. Similarly *Ceriodaphnia quadrangula* appeared during the treatment year and took the place of *C. reticulata*. *Diaptomus oregonensis* was a member of the plankton in both treatment and control years. *Cyclops bicuspidatus thomasi* disappeared from the lake, but this occurrence may have been unrelated to treatment (Strus 1976). Two warmwater cyclopoids, *Mesocyclops edax* and *Tropocyclops prasinus mexicanus*, replaced *C. b. thomasi*. Finally, the observed decline of *Chydorus sphaericus* may have resulted from elimination of blue-green algae blooms which benefit this species.

197. *Benthic macroinvertebrates.* For eutrophic reservoirs, the responses of benthic communities to artificial circulation have been

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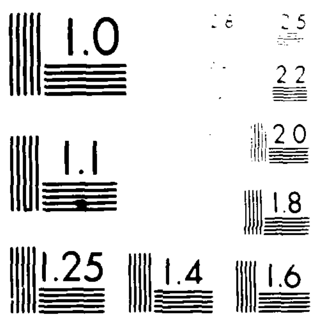
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relatively consistent, i.e., increases in macroinvertebrate biomass and taxonomic diversity (Table 12). Artificial mixing has dramatic effects on profundal zone communities, whereas little or no impact on biomass and composition of littoral fauna is evident (Barnes 1977). In two oligotrophic lakes, Parvin Lake and Section Four Lake, total population densities declined or stayed the same after treatment. In the profundal zone of Parvin Lake, average chironomid densities following destratification were only about 2.5 percent of pretreatment values (Lackey 1973c). Since chironomids were dominant members of the benthos in both lakes, population declines may have resulted from increased midge emergence due to warmer bottom temperatures during lake circulation.

198. The provisioning of favorable habitat in profundal areas by aeration allows increases in macroinvertebrate biomass by the following mechanisms:

- a. Growth of existing individuals or populations.
- b. Active migration of organisms from other areas.
- c. Passive transport of organisms by currents
- d. Colonization by sedimentation of eggs.

Although the first mechanism should produce a rapid response to environmental change, the last three may represent slow processes. In Parvin Lake and Section Four Lake, insect larvae and amphipods were abundant in littoral areas, but they did not invade the profundal zone soon after mixing. Although the data are limited to qualitative observations, Brown et al. (1971) found minimal change in the bottom fauna of Buchanan Lake during aeration. They suggested that profundal benthos of softwater lakes may take a year or more to respond due to slow colonization rates of oligochaetes and dipteran larvae.

199. The magnitude of increase in the abundance of profundal macrobenthos following circulation of Starodworski Lake ranged from 2.5 to 18.0 times pretreatment values (Sikorowa 1978). Chaoborus populations declined by 99 percent, however, being replaced by Chironomidae, Oligochaeta, Hydracarinae, and Heleidae. At Ham's Lake, higher benthic organism densities at the destratified site relative to a control site were also associated with a decline of Chaoborus and increases in other fauna, notably Hexagenia limbata, Ablabesmyia sp., and Coelotanypus sp. (Wilhm and McClintock 1978; also see Ferraris and Wilhm 1977). The number of species varied between 8 and 16 at the

TABLE 12. EFFECTS OF ARTIFICIAL CIRCULATION ON BENTHIC MACROINVERTEBRATES

Lake	Reference	Total Abundance	No. Species (or Diversity)	Chaoborus Abundance
Parvin Lake	Lackey 1973c	Varied[a]	0	
Section Four Lake	Fast 1971a	-		
University Lake	Weiss and Breedlove 1973	+[b]	+[b]	
Cox Hollow Lake	Wirth et al. 1970		+	-[c]
Stewart Lake	Barnes and Griswold 1975	+	+	-
Starodworski Lake	Sikorowa 1978	+	+	-
Ham's Lake	Wilhm and McClintoch 1978	+	+	-
Lake Catherine	Kothandaraman et al. 1979	+	+	
El Capitan Res.	Inland Fisheries Branch 1970	+	+	
Allatoona Res.	USAE 1973			-

[a] Chironomids -, others 0.

[b] Chironomids only.

[c] Also replacement of _C. punctipennis_ by _C. albatus_.

destratified site relative to only 4 at the control site, although Chaoborus remained dominant at both locations.

200. Artificial mixing also allowed habitat expansion for populations of chironomids, oligochaetes, clams, and nematodes at El Capitan Reservoir (Inland Fisheries Branch 1970). Aeration of University Lake resulted in elevation of chironomid density and diversity, especially in profundal areas near the air diffusers (Weiss and Breedlove 1973). The study design was confounded by different nutrient inputs during the control (low runoff) and aeration (high runoff) years however.

201. In five of the six lakes in which Chaoborus formed a significant component of the profundal benthos, larval abundance decreased after mixing (Table 12). In general, this was associated with replacement by other fauna especially oligochaetes and chironomids (e.g., Stewart Lake, Starodworski Lake, Ham's Lake). Thus, artificial destratification shifts the trophic structure of benthic communities by reducing predatory larvae, which feed primarily in the limnetic zone (cf. Pastorok 1980), and increasing resident detritivores.

202. Aeration of bottom strata removes the anoxic refuge normally exploited by Chaoborus spp., possibly exposing the larvae to intensified fish predation (Pastorok et al. 1980). Third and fourth instar larvae are a preferred food item for zooplanktivorous fish (Northcote et al. 1978; von Ende 1979). Moreover, fish predation is a critical factor determining the distribution of Chaoborus species, with smaller, less pigmented species being favored in the presence of visual planktivores (Stenson 1978; von Ende 1979). Intensified fish predation could explain the replacement of relatively large C. punctipennis by the smaller C. albatus in Cox Hollow Lake following aeration. On the other hand, Barnes (1977) found little change in fish predation or Chaoborus larvae during artificial circulation. He suggested that increased water turbulence, DO, and temperature over the profundal sediments of Stewart Lake during mixing stimulated larvae to spend more time swimming than burrowing, thus decrea[illegible] their numbers in bottom grab samples. Apparently, no one has studied changes in abundance of Chaoborus in both planktonic and benthic samples during artificial mixing experiments.

203. Fishes. In most cases, artificial circulation expands suitable habitat for fish (e.g., Gebhart and Summerfelt 1976; Brynildson and Serns 1977; Fast 1979a). Based on the limited data available, it appears that coldwater species respond to favorable conditions in the hypolimnion by increasing their depth distribution toward the lake bottom (e.g., Fast 1968, 1973b; Brynildson and Serns 1977), whereas warmwater species may remain in the surface layer and littoral areas (Barnes 1977) or expand their depth distribution (Gebhart and Summerfelt 1976).

204. Before aeration of Mirror Lake, trout and yellow perch were confined to the epilimnion and metalimnion (Brynildson and Serns 1977). During spring and late summer, the two fish species occurred above 5 m and 7 m, respectively, corresponding to a DO limit of about 3-4 mg/l. After destratification, trout were distributed throughout the lake to a maximum depth of 13 m. Yellow perch occupied the water column between 4 and 13 m.

205. Similar expansions of depth distributions have been observed for rainbow trout in Section Four Lake (Fast 1971a), for channel catfish, threadfin shad and walleye in El Capitan Reservoir (Fast 1968), and for yellow perch, bluegill, and crappie in Lake Calhoun (Shapiro and Pfannkuch 1973). At Arbuckle Lake during 1975 partial destratification increased available fish habitat (as defined by the 2 mg/l DO isopleth) from 53 percent of lake volume in August to 99 percent in September. Gizzard shad, freshwater drum, white crappie, and black bullhead all responded by expanding their depth distributions (Gebhart and Summerfelt 1976).

206. In contrast to the above studies, Barnes (1977) found that bluegills were not using the limnetic and profundal regions extensively either before or after artificial circulation. Although this result suggests little expansion of habitat, the depth distribution of fish was not studied in Stewart Lake.

207. Many researchers have postulated that artificial mixing increases individual growth rate and population yield of fishes, but little direct evidence is available to test these hypotheses (Barnes 1977). Wirth et al. (1970) concluded that fish harvest doubled from 1966-1969 during aeration of Cox Hollow Lake, although no improvement in growth was observed. Although Barnes and Griswold (1975) initially suggested that aeration improved bluegill growth in Stewart Lake,

Barnes (1977) later concluded that growth as measured by average condition factors in each age group was not altered significantly by artificial circulation. Thus, lakes which contained stressed fish populations (e.g., overcrowded and stunted centrarchids) might be especially slow to respond to habitat improvements.

208. Studies at Lake Arbuckle suggested an increase in growth of bottom fishes, but the results varied among species and years of study (Gebhart and Clady 1977). Possible statistical bias in back-calculating growth histories for previous years prohibits conclusive evaluation of mixing effects based on the Lake Arbuckle study.

209. The effects of aeration on fish survival appear to depend on an interaction between lake trophic state and seasonal timing of mixing. By aerating lakes during fall and winter, the usual "winterkill" in shallow productive lakes of the northern United States and Canada can be averted (e.g., Halsey 1968; Fike 1979). Application of mixing techniques after significant ice-cover and accumulation of high BOD in lower waters may aggravate natural fishkills, however, especially when aeration equipment is undersized (e.g., Patriarche 1961; Toetz et al. 1972).

210. The relationship between thermal stability, algal bloom collapse, and summer fishkills has been discussed above in regard to theoretical effects of mixing on dissolved oxygen levels. The results of artificial circulation experiments generally support the mechanism proposed by Papst et al. (1980) to explain natural depletion of oxygen in shallow, productive lakes on the Canadian prairie. For example, mixing of Lake Roberts in June during the development of an *Anabaena* bloom successfully elevated the dissolved oxygen content of the lake (R.S. Kerr Research Center 1970). In the July experiment, however, a combination of reduced photosynthetic activity in cloudy weather and an unusually high BOD caused by decomposing *Anabaena* created anoxic conditions throughout the lake precipitated a massive fishkill. Other aspects of seasonal mixing, species interactions and fish survival will be discussed in a later section (see "Importance of timing").

211. Adverse impacts on coldwater fisheries are also related to geographical location of artificially mixed lakes. During induced circulation of Puddingstone Reservoir in southern California,

favorable DO concentrations were maintained but mixing increased water temperatures above the maximum tolerated by rainbow trout (Fast and St. Amant 1971). Increases in the heat budget of artificially destratified reservoirs at southern latitudes therefore has the potential for elimination of coldwater fisheries. To the authors' knowledge, however, this effect has not been demonstrated.

Multiple discriminant analysis

212. For each response parameter (e.g., DO, algal density, pH), the initial objective is to maximize separation of lake response groups (e.g., +, -, 0, ?) by differentially weighting individual morphometric and mixing system variables in a discriminant function. If adequate discrimination is obtained, Multiple Discriminant Analysis (MDA) can be used to predict the response of a lake based on physical attributes of the lake and the aeration system.

213. Table 13 summarizes the results of MDA applied to diffused-air mixing systems and lake responses. An approximate statistical test using Wilks' lambda indicates that the first discriminant function was significant at $P < .05$ for biomass/chlorophyll *a* and epilimnetic pH. Air flow was an important variable in these two cases, but morphometric variables (surface area or mean depth) contributed the most to separation of groups. Aeration intensity (i.e., air flow divided by area or air flow divided by volume) was an important discriminant variable for a number of responses. Figure 8 is a plot of lakes on the first and second discriminant functions for the biomass/chlorophyll *a* response category. Asterisks mark the position of group centroids. Group 1 showed an increase in areal algal biomass or chlorophyll concentration; group 2 showed a decrease; group 3 lakes exhibited no change; and the response of group 4 lakes was variable or questionable. Note that the first discriminant function gave significant separation of groups but the second function did not.

214. For most response parameters, the percentage of total cases correctly classified by the discriminant function was unimpressive (Table 13). However, the poorly classified lakes were often in the variable (or questionable) response group. In many cases, the beneficial response group (e.g., increase in DO, decrease in algal density) was well classified. Also, several discriminant runs were close to statistical significance (e.g., algal density,

TABLE 13. RESULTS OF MULTIPLE DISCRIMINANT ANALYSIS OF LAKE RESPONSES TO ARTIFICIAL CIRCULATION

Response Parameter	P[a]	Total Cases Correct[b] (%)		Group +	Group -	Group 0	Group ?	Important Discriminant Factors
Algal density	0.07	67	No. %[c]	6 50	14 93	8 50	5 40	Q_A/A Q_A/V
Biomass/Chl a	0.04	83	No. %	5 100	6 83	6 83	6 67	Area Volume Q_A
Blue-greens	0.08	72	No. %	5 60	13 85	[7] [57]		Max. depth Area Mean depth
ΔT after	0.23	69	No. %	30[d] 80[d]	15[e] 47[e]	-- --	-- --	Q_A/A Q_A/V Volume
DO	0.09	83	No. %	33 94	[8] [38]			Q_A/A Q_A/A Air depth
Green algae	0.65	72	No. %	7 71	4 75	7 71	-- --	Q_A/V Q_A/A Area
Epilimnetic pH	0.04	85	No. %	-- --	9 100	[11] [73]		Mean depth Q_A
Gr:Bl-gr ratio	0.19	81	No. %	11 82	[10] [80]			Max. depth Mean depth
Secchi	0.34	84	No. %	4 100	10 80	[5] [80]		Volume Air depth

[a] Probability level associated with first Wilks' lambda; indicates significance of first discriminate function.

[b] Percent of all cases correctly classified.

[c] Percent of within-group cases correctly classified.

[d] Temperature differential between surface and bottom water less than or equal to 3° C.

[e] Temperature differential (ΔT) after mixing greater than 3° C.

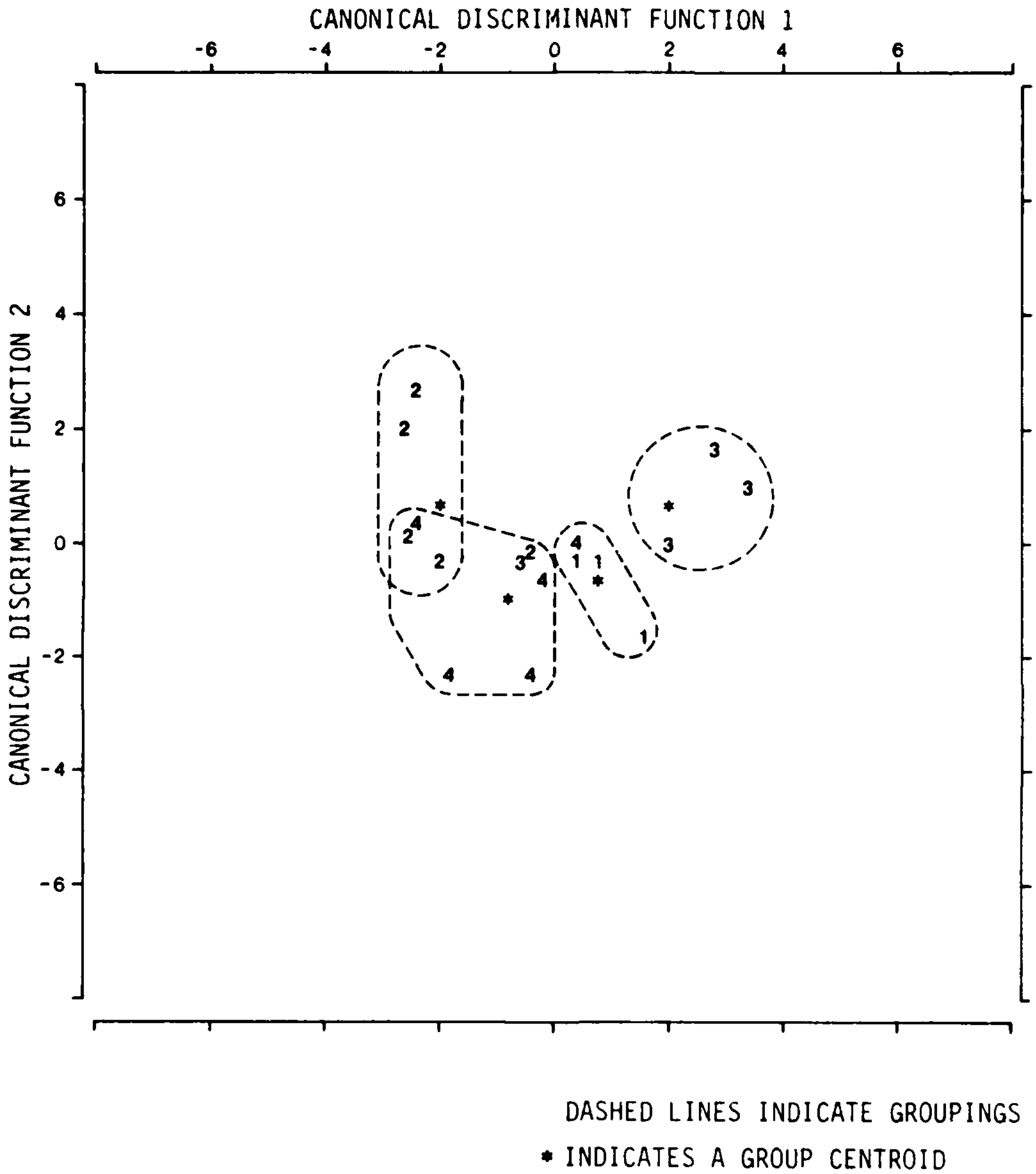

Figure 8. Plot of mixed lakes on the first two discriminant axes for the biomass/chlorophyll response category (see text for explanation of symbols).

blue-green algae, DO). These results suggest that MDA holds promise for prediction of lake responses to artificial circulation, but the data set on mixing experiments must be enlarged and improved before it can be applied in this way.

Partial mixing

215. Isothermal conditions throughout the lake basin were maintained in only a few mixing experiments (Table 5 above). The pattern of thermal stratification associated with partial mixing (e.g., see Figure 7 above) depends on the type of destratification device, the depth of air release, and the intensity of induced mixing as well as local climatic conditions.

216. Thermocline lowering. At Lake Arbuckle, an array of 16 Garton pumps with a capacity of 1,600 m^3/min was located near the lake surface to move water downward. This system failed to mix the 24.7 m-deep reservoir completely, but it did lower the thermocline and increase DO content of the lake (Toetz 1979a, b). These effects were localized in horizontal extent in 1974 (Toetz 1977a).

217. A diffused-air system will usually result in thermocline lowering rather than complete destratification if the depth of air release is significantly less than the maximum lake depth (e.g., Casitas Reservoir, Lake Calhoun). Nonetheless, intense aeration before high thermal stability is achieved may allow complete mixing even with a shallow air release depth (e.g., El Capitan Reservoir).

218. Although the data are limited, it appears that thermocline lowering produces less pronounced changes in hypolimnetic water quality and phytoplankton ecology than complete mixing does (Tables 5, 9, and 10). For example, biological changes in Lake Arbuckle after mixing have mainly been limited to decreases in primary production (Toetz 1977a, b; 1979a, b).

219. Surface microstratification. Fast (1979a) has pointed out the difficulty of achieving complete isothermy with diffused-air systems. Most destratification experiments employed low energy systems, with undersized air flow rates (Table 4; Lorenzen and Fast 1977). When excess thermal energy absorbed at the lake's surface is not distributed throughout the water column, microthermal stratification of 1 - 3°C provides algal populations a surface refuge with high light levels (Fast 1979a). The concentration of buoyant blue-green algae (e.g., *Aphanizomenon*, *Anabaena*) increases in surface

waters under these conditions (e.g., Thomas 1966; Drury et al. 1975; N.H.W.S.P.C.C. 1979). The influence on areal standing crop is unpredictable, depending on the thickness of the surface microlayer and the mode of growth limitation (see above, "Peak biomass vs. mixed depth"). In El Capitan Reservoir thermal microstratification near the surface during aeration accounted for an increase in primary productivity over pretreatment levels (Fast 1973a).

220. Aeration intensity of 0.72 m^3/min per 10^6 m^2 lake surface at Clear Lake was insufficient to maintain uniform vertical and horizontal distributions of the blue-green algae _Aphanizomenon_ and _Microcystis_, unless the wind velocity was greater than 5 m/sec.* Chlorophyll _a_ concentrations ranged from about 50 to 100 μg/l under well-mixed conditions, but surface blooms containing 500 - 2,500 μg/l were patchily distributed during calm periods. Temporary vertical stratification of the _Aphanizomenon_ population occurred at Kezar Lake when mechanical failures reduced aeration intensity from 3.88 to 1.94 m^3/min air per 10^6 m^2 lake surface (Haynes 1975). The benefits of aeration at Clear Lake were limited due to failure of an undersized destratification system to keep buoyant blue-greens mixed throughout the water column.**

221. _Localized destratification._ Localized mixing is commonly employed immediately upstream of reservoir outlet works for aeration of discharges (see below, "AERATION OF RESERVOIR RELEASES"). In other contexts, localized destratification results simply from the inability of mixing devices located in one area to induce mixing throughout a large reservoir. Spatial localization of treatment effects has been noted in Eufaula Reservoir (Bowles 1972), Allatoona Reservoir (USAE 1973), Lake Arbuckle (Toetz 1977a), Prompton Lake (McCullough 1974), Wahnbach Reservoir (Bernhardt 1967), and Casitas Reservoir (Barnett 1975; Smith 1980).

222. At Casitas Reservoir, oxygen concentrations declined away from the air diffuser in a horizontal direction. Water temperature

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* Personal communication, W.F. Rusk, October, 1980, University of California, Berkeley, California.

** Personal communication, A.J. Horne, October, 1980, Department of Sanitary Engineering, University of California, Berkeley, California.

profiles were suprisingly uniform, indicating complete horizontal mixing (Barnett 1975; Smith 1980). Temperature profiles at various locations in Vesuvius Reservoir suggested complete horizontal circulation there also (Irwin et al. 1966). Dissolved oxygen isopleths for Allatoona Reservoir indicated that diffused-air injection influenced oxygen levels as far as 6.4 km away but not as far as the 16-km station (USAE 1973).

223. Based on temperature and oxygen profiles at Eufaula Reservoir, Bowles (1972) concluded that aeration had pronounced effects on his Station 2, moderate impact at Station 4, and no effect at other stations. The aerator was located about 229 m upstream from the dam, under the influence of the withdrawal zone (Leach 1970). Station 2 was less than 1 km upstream of the aerator, Station 4 was about 2 - 2.5 km upstream, and the nearest station showing no apparent impact was more than 3 km from the air release site.

224. Finally, aeration suppressed the dissolution of manganese from profundal sediments throughout Wahnbach Reservoir (Bernhardt 1967), including sites more than 4 km from the aerator.

Importance of timing

225. The timing of destratification in relation to climatic conditions, chemical stratification, and seasonal succession of plankton plays a critical role in determining the impact of artificial destratification on lake biota. Despite the importance of timing, few investigators have systematically evaluated the effects of altering the onset of mixing relative to seasonal changes in community composition. The temporal relationships between destratification (natural and artificial), algal bloom collapse, and oxygen depletion have been discussed previously with respect to occurrence of fishkills. Variation in the onset of artificial mixing is discussed below with respect to species interactions in the plankton and alternative biological responses within a lake. When destratification timing is varied among lakes, analogous alternative responses should be observed.

226. The timing of artificial circulation relative to the chemical stratification cycle and lake productivity probably determines short-term responses of the phytoplankton community. Experiments with enclosed water columns (Shapiro 1973; Forsberg and Shapiro 1980a, b) and whole lake manipulations (Shapiro et al. 1975)

illustrate the potential role of hypolimnetic CO_2 and nutrients in eliciting dominance shifts among algal species in artificially destratified lakes. Slow aeration, which could be considered analogous to mixing before chemical stratification, mixes nutrients upwards without lowering pH, thereby promoting growth of the dominant blue-greens (Shapiro and Forsberg 1980b). Rapid destratification in lakes with high levels of CO_2 and nutrients in the hypolimnion lowers pH of the surface layer and induces the shift from blue-green species to green algae.

227. The importance of timing in application of aeration/circulation methods is well illustrated by a series of experiments performed at Heart Lake by the Ontario Ministry of the Environment (Nicholls et al. 1980).* In 1975, the lake was artificially circulated throughout the summer with 2.38 m^3/sec air per 10^6 m^2 of lake surface. At the start of aeration in late June, blue-green algae, predominantly Aphanizomenon flos-aquae and Anabaena planctonica were already well established in the lake. Treatment resulted in a decrease in the abundance of blue-greens but only a slight shift in the species composition of phytoplankton. As Daphnia pulex invaded and became a dominant species, grazing pressure on the phytoplankton community probably intensified (Strus 1976).

228. During the following year, treatment was initiated earlier (April), before the development of a strong blue-green association. The usual blue-green bloom never materialized; instead the phytoplankton was dominated by chlorophytes and cryptomonads, generally edible forms of algae. Later in the summer, however, a massive bloom of Ceratium hirundinella ensued, possibly as a result of the advantages gained by its resistance to zooplankton grazing (Strus 1976; also see Porter 1975). The Ceratium outburst led to oxygen depletion throughout the lake and a subsequent fishkill (Nicholls et al. 1980).

229. The experiments were continued for two more years, and the results generally confirmed the findings of earlier studies.* In

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* Personal communication, K.H. Nicholls, October, 1980, Ontario Ministry of the Environment, Ontario, Canada.

1979, when aeration was initiated after the establishment of the blue-green association, the response pattern resembled the 1975 trends. But when aeration began before the blue-green domination in 1980, the shift to green algae and cyryptomonads occurred as in 1976. When dissolved oxygen concentrations started decreasing during the bloom of Ceratium in July 1980, two more aerators were brought into service, boosting the air flow to 6.34 m^3/min per 10^6 m^2 of lake surface. Anoxia did not occur and a fishkill was prevented.

230. Nicholls* feels that the presence of blue-greens discourages development of the Ceratium bloom through some competitive interaction. Alternatively, it seems possible that late aeration precludes enough time for the selective grazing pressures to force the community away from the green-cryptomonad state toward a monopoly of the herbivore-resistant form, Ceratium. In any case, early aeration of a deeper lake produced a shift from blue-green algae to green algae but did not result in the massive Ceratium populations observed in Heart Lake.* The exact factors responsible for this difference are unknown. Light limitation in the deeper lake could play a role; or greater dilution of phytoplankton and herbivores might reduce the intensity of selection on the algal association.

Long-term effects of mixing

231. There has been essentially no evaluation of the long-term impact of artificial mixing on the physicochemical conditions and biological communities of lakes. Circulation experiments have been carried out for several years in Kezar Lake, Ham's Lake, Heart Lake, and Lake Arbuckle (Table 4 above), but long-term trends have not been analyzed in detail. At Lake Arbuckle and Ham's Lake, there is no apparent pattern of change in lake responses from year to year (Tables 5 and 9). Phytoplankton blooms in Kezar Lake during the 1968 - 1971 period were of progressively shorter duration, but during 1972 - 1974 they showed a gradual return to the same level of persistence as before treatment (N.H.W.S.P.C.C. 1979).

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* Personal communication, K.H. Nicholls, October, 1980, Ontario Ministry of the Environment, Ontario, Canada.

232. The slow growth rate and generation times of fishes imply a delayed response to artificial circulation relative to the rapid manipulations possible with lower trophic levels. Since most of the experimental studies of mixing were limited to one or two years, fish populations may not have reached equilibrium with the modified lake environment. As mentioned above, previously stressed populations might be especially slow to respond to habitat improvements. In projects continued for several years, the impact on fish populations was rarely considered for more than 1 - 2 yr.

PART III: HYPOLIMNETIC AERATION AND OXYGENATION

233. The basic goal of hypolimnetic aeration/oxygenation is to increase dissolved oxygen concentrations in lower lake waters without disrupting the normal pattern of thermal stratification. As an alternative to artificial circulation, hypolimnetic techniques preserve the natural heat budget and maintain a coldwater resource. In most hypolimnetic treatment systems, bottom waters are not brought into extensive contact with the atmosphere; since oxygen transfer is mainly limited to the interface between injected bubbles and hypolimnetic water, oxygenation by hypolimnetic treatment is slower than by artificial circulation.

Hypolimnetic Treatment Methods

234. Fast and Lorenzen (1976) proposed the following categories of hypolimnetic aeration/oxygenation: (a) mechanical agitation; (b) pure oxygen injection; and (c) air injection systems including full air-lift design, partial air-lift design, and downflow air injection system. Speece (1971) proposed several unconventional designs, but these have not received wide use. Fast et al. (1976) and Lorenzen and Fast (1977) compared different designs and reviewed cost considerations. Although hypolimnetic aerators are not strictly comparable with destratification systems, the best oxygenation capacities for hypolimnetic aeration (about 0.95 kg O_2/kWh) fall in the middle of the range for mixing systems (Tolland 1977).

Mechanical agitation

235. Aeration by mechanical agitation generally involves withdrawal of hypolimnetic water, aeration by discharge into a splash basin located onshore or at the lake surface, and return of aerated water to the hypolimnion. The first reports of hypolimnetic aeration described the mechanical agitation system used at Lake Bret, Switzerland (Mercier and Perret 1949; Mercier and Gay 1954; Mercier 1955). These systems have been used infrequently, possibly because they are relatively inefficient in terms of oxygen dissolution per unit of energy input.

Pure oxygen injection

236. The side stream pumping (SSP) system was the first successful method of hypolimnetic oxygenation (Fast et al. 1975b; Fast and Lorenzen 1976; Overholtz et al. 1977). Water is withdrawn from the hypolimnion and brought to shore. Pure oxygen is injected into a high-pressure discharge line which returns withdrawn water to the hypolimnion. Almost all the oxygen is dissolved before it leaves the discharge pipe (Fast and Lorenzen 1976).

237. Speece et al. (1973, Speece 1975) suggested injection of oxygen through coarse bubble diffusers located in the hypolimnion as a means of oxygenation. Presumably, if the hypolimnion is deep enough, the bubbles will be dissolved before reaching the thermocline. Fast and Lorenzen (1976) discuss potential problems with this approach, including accidental mixing of hypolimnetic water with upper layers, incomplete mixing within the hypolimnion, localized anoxia, and expense of oxygen importation and storage.

238. Speece (1971; Speece et al. 1973) also proposed the downflow-bubble-contact-aerator. As hypolimnetic water is pumped downward within a funnel-shaped tube, diffused oxygen bubbles are released below the pump. As the bubbles are forced downward by the high water velocity they oxygenate the water. Once they reach the bottom of the funnel, the bubbles are composed mainly of N_2 gas, which has diffused into the bubbles. Therefore, waste gases rise to the surface and could cause undesirable mixing (Fast and Lorenzen 1976).

239. Whipple et al. (1975) described a hypolimnetic oxygen injection system which was installed in Spruce Run Reservoir. The system was similar to a partial air-lift design (see "Air injection systems"). The failure of the system to operate properly may have been due in part to an improper experimental design (Fast and Lorenzen 1976).

Air injection systems

240. Full air-lift systems employ diffused air to bring water to the surface in a vertical tube. After the separation of air bubbles and water, the water is returned to the hypolimnion without mixing with the surface layer. Partial air-lift designs aerate hypolimnetic water without transporting it to the surface; water and waste air separate at depth. Partial air-lift systems are described by Fast et al. (1975a), Fast and Lorenzen (1976), and Lorenzen and

Fast (1977). Full air-lift designs are given by Bernhardt (1967, 1974), Fast (1971a), Bengtsson and Gelin (1975), Fast and Lorenzen (1976), Lorenzen and Fast (1977), and Taggart and McQueen (in press). Both types of air-lift systems upwell and aerate water by injection of compressed air at the bottom of a vertical tube with opening(s) to the hypolimnion. After rising to the top of the tube, waste gases along with some CO_2, H_2S, and NH_3 are vented to the atmosphere.

241. Although partial lift aerators have greater effluent oxygen concentrations, they probably oxygenate less water volume and dissolve less total oxygen than the full air-lift devices. The shorter the vertical tube is, the lower the efficiency of the aerator will be. With a short "travel time," more air will be vented; hence much of the energy used to compress the air will be lost in waste discharge. Fast et al. (1976) showed that a full air-lift design produces the least expensive aeration device considering overall costs of construction, installation, and operation. In terms of energy consumed to dissolve a given amount of oxygen, it was almost twice as efficient as the other systems examined (SSP, the LIMNO partial air-lift device, and Bernhardt's full air-lift aerator).

Theoretical Aspects

Physical

242. As indicated in the review by Fast and Lorenzen (1976), there are a number of hypolimnetic aeration devices and methods. However, most have been experimental and very little theory describing the hydraulics, gas transfer, or circulation has been developed and verified.

243. Other than proprietary devices, the only theoretical approach to design was presented by Lorenzen and Fast (1977). Although their approach is simplified and untested, it does provide interim guidance. The approach is based on a consideration of hypolimnetic volumes and oxygen consumption rates combined with computations of air needed to both meet the oxygen demand and "pump" the required amount of water.

244. Hypolimnetic volumes and oxygen demands are best determined from bathymetric maps coupled with temperature and oxygen profile data. Consideration should be given to the fact that some

thermocline erosion will occur and the hypolimnetic volume may increase during aeration. Oxygen consumption rates should be determined from field data by plotting total oxygen content against time and using the steepest part of the curve.

245. The minimum required oxygen input is that amount necessary to meet the demand. The required air flow is then computed based on hydraulics of fluid flow in the device. Generally, less air is required for larger diameter pipes. The pipe size and air flow are then selected such that the air flow is greater than minimum requirements, required water flow is met, and costs are minimized.

Chemical

246. The qualitative effects oi hypolimnetic aeration/oxygenation in a stratified eutrophic lake should resemble the chemical changes induced in lower waters by artificial circulation. Thus, hypolimnetic DO concentrations should increase following treatment, whereas the levels of Fe^{++}, Mn^{++}, H_2S, NH_4^+, CO_2, and other chemicals associated with anoxic conditions should decline. A rise in hypolimnetic NO_3^- should accompany the decrease in NH_4^+, assuming an influence of nitrification in oxygen-rich waters (e.g., Bengtsson and Gelin 1975; Garrell et al. 1977). Unlike strong artificial circulation, hypolimnetic aeration will not create isochemical conditions throughout the lake. The depth profiles of most chemicals after hypolimnetic treatment will depend on site-specific conditions before aeration and the interaction of physical, chemical, and biological parameters. Hence, depth profiles are impossible to predict in general.

247. Several potential problems with dissolved gases may remain after hypolimnetic aeration/oxygenation. In lakes where BOD is particularly intense throughout the water column, the depth profile of DO during treatment may exhibit a metalimnetic minimum. Although treatment *per se* does not cause the depleted oxygen zone, it is ineffective at alleviating low DO conditions above the hypoliminion. As with artificial circulation using diffused air, hypolimnetic aeration may elevate nitrogen gas (N_2) levels in bottom waters, causing supersaturation relative to surface pressures. However, N_2 concentrations in the hypolimnion are normally at supersaturation relative to the surface (see above, "ARTIFICIAL CIRCULATION"). The role of artificial aeration as a cause of gas bubble disease in fishes is unclear; but no serious problem has been observed thus far.

248. Although pH of the hypolimnion is expected to rise after treatment, the pH of the epilimnion should remain about the same as before. Other chemical conditions in the epilimnion should exhibit minimal short-term changes following hypolimnetic aeration/oxygenation.

249. Although nitrate concentrations in the hypolimnion may rise because of nitrification, phosphate concentrations should decline rapidly upon oxygenation (see discussion under "ARTIFICIAL CIRCULATION"). Moreover, hypolimnetic treatment has a greater potential for reduction of internal phosphorus loading than does artificial mixing. Hypolimnetic aeration creates an oxidized microzone at the mud-water interface without stimulating decomposition by raising sediment temperatures. Nevertheless, the long-term influence on nutrient release rates depends on the balance among conflicting factors such as primary production in upper waters, sediment composition, redox levels, and benthic fauna. The species composition and abundance of benthic fauna invading the profundal zone after treatment will have an important role in determining internal loading. Finally, the overall effectiveness of hypolimnetic aeration in controlling nutrient availability to phytoplankton is related to the ratio of internal loading to external loading. As nutrient influx from the watershed becomes more important, the effectiveness of manipulating internal nutrient dynamics to limit plankton growth is reduced.

Biological

250. Presumably, the biological changes induced by hypolimnetic aeration or oxygenation will not be as extreme as those observed after whole lake mixing. The impact on phytoplankton in particular will be limited mainly to indirect effects on algal abundance via regulation of internal loading or modification of animal communities. The distribution of some phytoplankton, e.g., those few species that occupy hypolimnetic strata, may be disrupted by internal mixing of the hypolimnion. But by and large, the normal vertical profile of phytoplankton will remain intact following hypolimnetic aeration. By preserving the natural thermal structure of the lake, aeration of bottom layers fails to increase mixed depth and induce light-limitation of algal growth. Unlike artificial destratification, hypolimnetic treatment does not mix CO_2 and nutrients into the upper

waters. Thus, it is not expected to produce pH-associated shifts in dominance among phytoplankton species.

251. As mentioned previously, hypolimnetic aeration may reduce internal loading of phosphorus, but the ultimate effect on phytoplankton depends on the relative rates of internal versus external loading. When internal loading is critical, the greatest effect of aeration on algal growth should be observed during autumn, at a time when natural destratification would normally recycle hypolimnetic nutrients to the upper waters. In the absence of this natural regeneration mechanism, any phytoplankton bloom normally stimulated by autumnal turnover would be curtailed. Note that decreases in autumn phytoplankton of aerated lakes should not be expected when natural destratification limits algal growth through increases in mixed depth and restriction of access to high light environments.

252. Long-term effects of hypolimnetic aeration on internal nutrient cycling might be more pronounced. For example, continued aeration might modify sediment composition such that surficial mud layers contain less organic matter. Under these conditions, lowered phosphorus release rates are expected (Holdren and Armstrong 1980; Frevert 1980).

253. Hypolimnetic aeration/oxygenation should allow habitat expansion for organisms which are intolerant of low oxygen environments. Thus, the depth distribution of zooplankton, benthic macroinvertebrates, and fish should increase following treatment. In the event that some portion of the community occupied lower strata before aeration, then the "center of mass" of the depth profile should shift downwards after hypolimnetic aeration. Coincident with habitat expansion of obligate aerobes, one expects to observe a decline of those species which characterize oxygen-poor environments. The exact mechanisms characterizing species replacements will relate to site-specific competitive and predatory interactions.

254. The abundance of zooplankton should increase following hypolimnetic aeration/oxygenation. Although hypolimnetic treatment produces little direct change in food resources for zooplankton, the manipulation of predation regimes is similar to that expected with artificial circulation. By providing increased habitat volume for both fish and zooplankton, aeration essentially dilutes species

populations and reduces the intensity of predator-prey interactions (cf. Fast 1979a; Shapiro 1979). In addition, the dimly lit hypolimnion serves as a daytime refuge for large-bodied zooplankton.

255. Following hypolimnetic treatment, an increase in the abundance and diversity of benthic macroinvertebrates is also expected, especially in the profundal zone. The interactions between fish, zooplankton, and benthic prey are not well understood. However, shifts in fish diets from zooplankton to littoral zone insects have been observed, and littoral prey are assumed to be preferred over zooplankton by adult fishes of facultative planktivore species (Galbraith 1967; Whiteside et al. 1980). It is possible that increases in benthic prey after aeration account for decreased predation intensity on open-water prey.

256. Herbivorous zooplankton may be further released from predatory control by fish specialization on carnivorous invertebrates which are generally larger, preferred food items (Confer and Blades 1975). In the case of some Chaoborus species, an anoxic hypolimnion provides a critical refuge from vertebrate predation (Fast 1971a; von Ende 1979). Aeration of bottom waters subjects the larvae to intense fish predation. With the increased availability of alternative preferred items, fish are expected to feed to a lesser extent on the herbivorous zooplankton (Confer and Blades 1975). Thus, the carnivorous invertebrates common to the open water zone serve as an ecological buffer, in a sense protecting herbivorous zooplankton from extreme fish predation.

257. In summary, aeration of bottom waters can lead to profound shifts in predatory interactions within lake communities. Large herbivorous zooplankton may increase in abundance following treatment, but the even larger carnivorous invertebrates may be decimated by fish predation. Smaller carnivorous species might replace their larger ecological analogs as a result of reduced competition. If so, the elevation of predation pressure on small herbivores would further shift the zooplankton size distribution toward large-bodied herbivores; e.g., daphnid species.

258. Unlike artificial circulation, hypolimnetic treatment fails to dilute algal toxins and zooplankton-phytoplankton interactions. Abundant zooplankton populations could concentrate in the upper waters during nighttime foraging periods, causing heavy

grazing pressure on phytoplankton relative to pretreatment conditions. The importance of nutrient regeneration from herbivores might be expected to increase with more abundant zooplankton (Lehman 1980b), but this effect is counteracted by the increase in mean herbivore size after hypolimnetic aeration. Larger zooplankton release less phosphorus per unit body weight than the smaller forms do (Bartell and Kitchell 1978).

259. The impact of hypolimnetic aeration/oxygenation on fisheries is perhaps the most predictable of all biological responses. By oxygenating bottom waters without destroying thermal stratification, hypolimnetic treatment creates a suitable habitat for trout and other coldwater fishes. In northern lakes, the changes induced by hypolimnetic treatment are expected to be similar to those predicted for artificial mixing; i.e., habitat expansion of coldwater species especially with possible improvements in growth rates and yields (see "ARTIFICIAL CIRCULATION"). Coldwater fish are expected to be found throughout the water column in aerated northern lakes since epilimnetic temperatures during summer would be suitable for trout survival (e.g., Northcote et al. 1964). In southern lakes, however, artificial circulation may lead to the demise of coldwater fisheries by modifications of thermal structure and heat budget (see above). In contrast, hypolimnetic aeration maintains habitat for coldwater and warmwater species, creating a two-story fishery (Fast 1975, 1979a). Hypolimnetic aeration of deep reservoirs may even allow a three-story fishery, with warmwater species occupying the uppermost layers, coldwater species living mainly in the hypolimnion, and intermediate species distributed mainly in the metalimnion.

260. In cases where a metalimnetic minimum of oxygen persisted after hypolimnetic treatment, a three-story fishery might be impossible. A metalimnetic oxygen deficit will not necessarily prevent fish movements between upper and lower waters (Serns 1976; Garrell et al. 1978).

261. Fish may have a critical role in regulating phosphorus availability in lakes (Nakashima and Leggett 1980; also see "ARTIFICIAL CIRCULATION"). However, lack of conclusive evidence regarding the mechanisms underlying observed fish-nutrient interactions (e.g., Andersson et al. 1978; Henrikson et al. 1980) and phosphorus supply routes precludes valid generalizations about the influence of aeration on these processes.

Review of Hypolimnetic Aeration/Oxygenation Experiences

262. The available information on hypolimnetic aeration/oxygenation consists of 15 detailed case studies on physical, chemical, and biological responses to treatment in 11 lakes. Although many additional experiments have been carried out, especially in European lakes where LIMNO aerators have generally been used, the data on lake responses are limited.

Lake characteristics and hypolimnetic systems

263. The morphometric characteristics of selected lakes and operational aspects of their hypolimnetic aerators are summarized in Table 14. The lakes varied from the shallow Spruce Knob Reservoir (5.7-m maximum depth) and Tory Lake (10-m maximum depth) to the relatively deep Wahnbach Reservoir (43-m maximum depth), which also has the largest surface area (214.5 ha). Although the volume of Wahnbach Reservoir is about 5.3 times greater than that of Jarlasjon, the aeration intensity at the latter site was about 2.5 times larger than air flow in the German reservoir. To compare measures of aeration intensity among lakes, however, it is desirable to normalize air flow rate for effects due to differences in hypolimnetic volume and BOD (or oxygen depletion rate). Unfortunately, this data is unavailable for most of the case studies examined.

Physical responses

264. The physical and chemical effects of hypolimnetic aeration/oxygenation are summarized in Table 15. Changes in thermal profiles and heat budget after treatment are minimal. Unlike artificial circulation, hypolimnetic aeration/oxygenation preserves cold temperatures in bottom waters. In general, successful operation of hypolimnetic aerators elevated temperatures in the hypolimnion by $4^{o}C$ or less (Table 15). The $6^{o}C$ increase of hypolimnetic temperature in Tory Lake may be partly related to temporary leakage through the vertical tower of the aerator, but this is difficult to evaluate without data from a control year. Water leakage through the aerator tower in the Hemlock Lake experiment raised the temperature of the hypolimnion by more than $2^{o}C$ per week (Fast 1971a). In that respect, the Hemlock Lake system malfunctioned throughout the experiment, and the lake destratified early.

TABLE 14. SELECTED LAKES AND THEIR HYPOLIMNETIC AERATION SYSTEMS

Lake	Location	Reference	Shape	Depth (m) Max.	Mean	Air	Vol $\times 10^{-6}$ (m^3)	Area (ha)	Aeration Intensity Q_{air} (m^3/min)	Start Date	Duration (mo)
Lake Waccabuc	New York	Fast et al. 1975a Garrell et al. 1977	elliptical	13		13	4.053	53.6	7.93	7/15/73 5/14/74	3 5.5
Mirror Lake	Wisconsin	Smith et al. 1975	elliptical	13.1	7.6	12.8	0.400	5.3	0.45	8/10/72 1/30/73 6/21/73	1 1 2.2
Larson Lake	Wisconsin	Smith et al. 1975	Subcircular	11.9	4.0	11.9	0.188	4.8	0.45	2/ 2/73 4/15/73	1.5 5
Jarlasjon	Sweden	Bengtsson and Gelin 1975	elongate	24	9.3	24	7.8	84	22.8	5/26/70	4.2
Spruce Run Res.	New Jersey	Whipple et al. 1975	irregular	13.1		12.2			0.15	5/25/73 5/15/74	2 >2
Hemlock Lake	Michigan	Fast 1971a	circular	18.6		18.6		1.8	2.8	6/13/70	
Ottoville Quarry	Ohio	Fast et al. 1975b Overholtz et al. 1975	rectangular	18		18	0.063	0.73	0.11[a]	7/ 7/73	3
Wahnbach Res.	W. Germany	Bernhardt 1967, 1974	elongate	43	19.2		41.63	214.5	4.02 9	7/ 7/66 5/71 on	4.3 4-5/yr
Spruce Knob Res.	W. Virginia	Hess 1977 LaBaugh 1980	subrectangular	5.7	2.1	5.2	0.224	10.5	1.3	7/15/74[b] 5/ 1/75	2 5
Lake Ghirla	Italy	Bianucci and Bianucci 1979	elliptical	14	8	14	2	24.5		7/18/76	2.7
Tory Lake	Ontario	Taggart and McQueen In Press	elliptical	10	4.5	9.0 8.5	0.055	1.23	3.54	5/78 5/79	5 6

[a] *Injection rate for pure oxygen, sidestream pumping.*

[b] *Mechanical pump.*

TABLE 15. RESPONSES TO HYPOLIMNETIC AERATION

Lake	Hypolimnion Response[a]							
	T (°C)	DO	PO_4	TP	NO_3	NH_4	Fe Mn	pH
Lake Waccabuc	0	+	$\bar{0}$		+	-		
Mirror Lake 1972	+3	0	-[b]	0[b]	0	0[b]		
Mirror Lake 6/73		0	+	+		+		
Larson Lake	0	+	-	-		-		0
Jarlasjon	+1	+	-	-	+	-	-	
Spruce Run Res. 1973	0	+	0		0	-	-	0
Spruce Run Res. 1974	0	+	0		0	-	-	0
Hemlock Lake	+2°/wk[c]	+						+
Ottoville Quarry	+3	+						
Wahnbach Res.	+4	+	-	-	+	-	-	
Spruce Knob Res. 1974	+1-3	+	-	-	0			0[b]
Spruce Knob Res. 1975		+	-	-	+			-
Lake Ghirla	+2	+						
Tory Lake 1978	+6	+0		-		-		-0
Tory Lake 1979	+4	+0		-		-		-0

[a] Response parameters: DO = Dissolved O_2
PO_4 = Phosphate
TP = Total Phosphorus
NO_3 = Nitrate
NH_4 = Ammonium
Fe = Iron
Mn = Manganese

Direction of change in hypolimnetic concentration:
+ = Increase
- = Decrease
0 = No significant change

[b] Change in response parameter possibly unrelated to treatment.

[c] Eventual destratification due to water leakage through walls of aerator tower.

265. Little data on other physical response parameters (e.g., turbidity, seston, transparency) are available. Fast (1971a) observed first a decrease and then an increase in Secchi transparency during aeration of Hemlock Lake relative to control year values. Because of some mixing of hypolimnetic waters into the surface layer, however, these results cannot be considered representative of other hypolimnetic aeration/oxygenation experiments.

Chemical responses

266. Oxygen content of the hypolimnion has been successfully increased in almost all hypolimnetic aeration/oxygenation experiments (Table 15). As a result of treatment, DO concentrations in bottom waters rose from 0 mg/l or near-zero immediately before aeration or during a control year to as much as 7 - 8 mg/l in Lake Waccabuc, Jarlasjon, Larson Lake, Wahnbach Reservoir, Hemlock Lake, and Lake Ghirla. Injection of pure oxygen into the hypolimnion of Ottoville Quarry elevated DO concentrations to 20 mg/l or more, without apparent adverse effects on fish. Compressed air injection in Spruce Knob Resevoir during 1974 maintained DO at 1 - 4 mg/l in an initially anoxic hypolimnion. Mechanical aeration during 1975 increased oxygen transfer efficiency and kept hypolimnetic DO concentrations at 1 - 5 mg/l. During the 1978 and 1979 experiments in Tory Lake, aeration initially raised the oxygen content of bottom waters from < 1 mg/l to slightly above 4 mg/l. However, by mid-July BOD exceeded the oxygenation capacity of the system, and oxygen declined to < 0.5 mg/l. In Mirror Lake and Spruce Run Reservoir, the aerators were undersized, and hypolimnetic DO never exceeded 1.7 mg/l and 3 mg/l, respectively.

267. Anoxic zones developed within the metalimnion during treatment of Lake Waccabuc (Garrell et al. 1977), Jarlasjon (Bengtsson and Gelin 1975), Larson Lake (Figure 9; Smith et al. 1975), and Tory Lake (Taggart and McQueen in press). Only a slight oxygen minimum was detected at the thermocline during late July and August 1975 in Spruce Knob Reservoir (LaBaugh 1980). If the aerator is undersized, e.g., 1973 experiment at Spruce Run Reservoir, anoxic zones may develop above and below the water discharge tubes of the aerator (Whipple et al. 1975). A boost in aerator capacity will probably not alleviate anoxic conditions in the metalimnion without disrupting the thermocline.

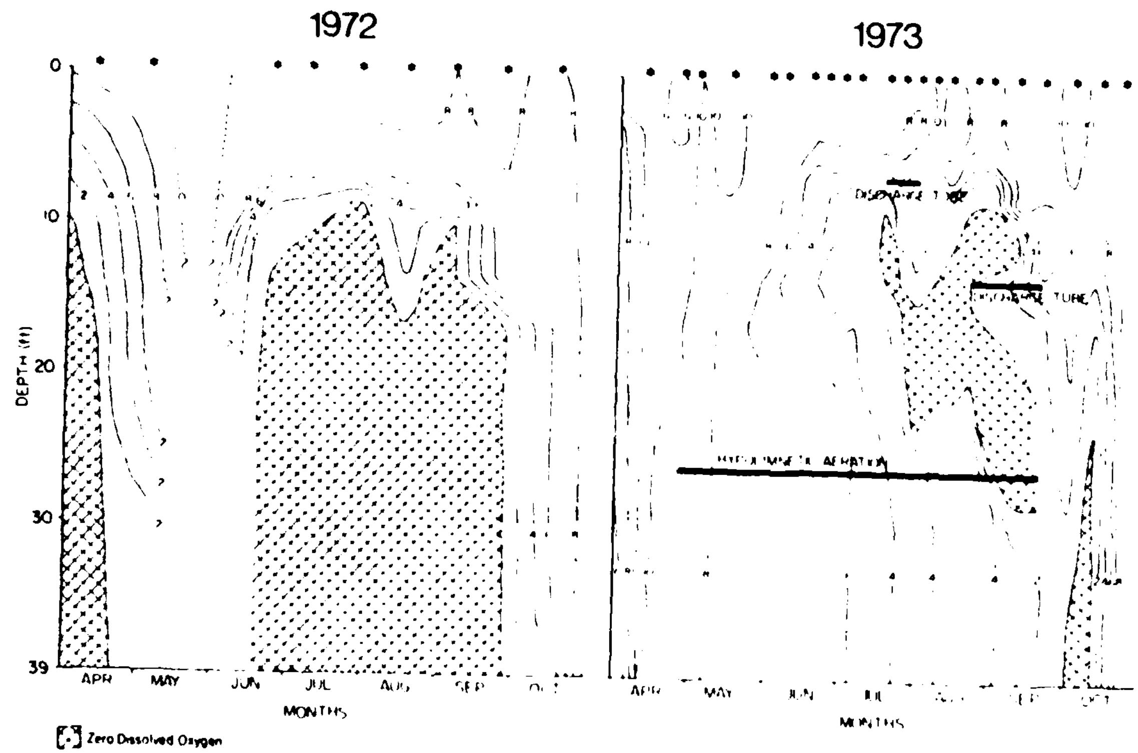

Figure 9. Larson Lake dissolved oxygen isopleths in mg/l. Sampling dates are indicated by asterisks (after Smith et al. 1975).

268. The ecological significance of a metalimnetic oxygen deficit is unclear. Some aeration studies indicate that a metalimnetic minimum in DO concentrations serves as a barrier to fish movements (Bengtsson et al. 1972; Taggart and McQueen in press), whereas other work indicates that trout and yellow perch migrate through low DO zones (Whipple et al. 1975; Serns 1976). A hypoxic metalimnion in Tory Lake was toxic to caged fish and prevented extensive vertical movements of both zooplankton and minnows (*Pimephales promelas*).* Moreover, a *Filinia longiseta* population which became established in the hypolimnion was isolated from another rotifer population in the epilimnion. The effectiveness of a hypoxic metalimnion as a barrier to fish and zooplankton movements may depend on high concentrations of toxic chemicals rather than low DO per se. For example, high levels of H_2S and NH_4^+ were observed in the metalimnion of Tory Lake (Taggart and McQueen in press).

269. To the authors' knowledge, there has been only one study of nitrogen gas supersaturation as related to hypolimnetic aeration. Fast et al. (1975a) found that N_2 concentrations in bottom waters of Lake Waccabuc increased from near saturation to 150 percent saturation (relative to surface hydrostatic pressures) after 80 days of system operation. Although higher levels of N_2 supersaturation are possible with longer periods of aeration or greater release depths (Fast 1979a, b), 150 percent supersaturation would be high enough to cause severe mortality when fish are acclimated to 100 percent saturation or less. At Lake Waccabuc, fish may have adjusted their behavior to avoid discomfort associated with gas bubble formation in tissues (Fast et al. 1975a). Since hypolimnetic waters were not released to a stream, potential downstream fishkills were avoided.

270. Calculations indicate that the hypolimnetic aerator in Wahnbach Reservoir produces up to 160 percent supersaturation of nitrogen gas (Bernhardt 1974). Nevertheless, divers have observed fish in the zone of ascending air bubbles, and Bernhardt (1974) claims there have been no adverse impacts on fish populations due to N_2 supersaturation.

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271. Like artificial circulation, hypolimnetic aeration/oxygenation can effectively reduce concentrations of $PO_4^{\equiv}$, TP, NH_4^+, Fe^{++} and Mn^{++} in bottom waters (Table 15). Concentrations of other chemicals associated with anoxic conditions, e.g., H_2S, CO_2, CH_4 are also controlled by aeration (Smith et al. 1975; LaBaugh 1980; Taggart and McQueen in press). A rise in hypolimnetic NO_3^- generally accompanies the decrease in NH_4^+, suggesting increased nitrification in oxygenated waters (Bengtsson and Gelin 1975; Garrell et al. 1977). In model sediment-water systems, Chen et al. (1979) found that nitrification was rapid when previously anoxic waters were aerated. After about 23-26 days of aeration, NH_4^+ in the overlying water had declined from 8 mg/l to trace levels; NO_3^- increased from about 0 mg/l at 17 days to a maximum of 6.5 mg/l after 30 days. Although NO_3^- disappears from the hypolimnion of Cox Hollow Lake during aeration, calculations indicate there is not a large net loss of nitrogen from the system (Chen et al. 1979). As much as 60 percent of the nitrate may be immobilized in the sediments where it is biologically assimilated or chemically reduced. Thus, nitrogen is eventually recycled to the water column from sediments and vice versa, rather than being lost to the lake as N_2 gas. Chen et al. (1979) concluded that aeration will not result in a net loss of nitrogen from Cox Hollow Lake, although other lakes may exhibit less efficient retention mechanisms.

272. Although hypolimnetic aeration effectively reduces phosphate concentrations (Table 15), its influence on nutrient availability and rate of supply to aquatic plants depends on a complex of interacting factors discussed above (see "Theoretical Aspects"). In the long term, phosphorus regeneration from profundal sediments may be diminished by artificial oxidation of surficial mud layers. Compared with whole lake mixing, hypolimnetic aeration shows more promise for controlling internal nutrient fluxes.

273. Finally, external nutrient loading or decomposition of autochthonous production can mask the effect of aeration on internal nutrient dynamics. During aeration of Lake Waccabuc, phosphorus concentrations declined significantly the first year, but increased greatly during the second year of treatment (Garrell et al. 1977). Input of phosphorus from the watershed to the lake was probably much greater during the second aeration experiment. During the summer of

1973 at Mirror Lake, hypolimnetic aeration failed to prevent increases in total phosphorus and phosphate. Smith et al. (1975) suggested that large numbers of dead Oscillatoria cells mixed throughout bottom waters accounted for the observed changes in phosphorus.

Biological responses

274. The data on the biological effects of hypolimnetic aeration/oxygenation are limited to a handful of recent studies. These results generally support the predicted outcomes of treatment discussed above. Nevertheless, some interesting deviations emphasize the extreme importance of site-specific community structure and function in determining qualitative as well as quantitative responses.

275. Plankton. The few studies of phytoplankton during hypolimnetic aeration indicate minimal impact on chlorophyll concentrations (Whipple et al. 1975; LaBaugh 1980), algal abundance (Confer et al. 1974), species composition (Smith et al. 1975), and primary production (Whipple et al. 1975; LaBaugh 1979, 1980). Although LaBaugh observed decreased chlorophyll concentrations during 1975 in Spruce Knob Lake, he attributed this to natural destratification during June. Increased primary productivity and shifts in phytoplankton species composition during a summer of aeration in Hemlock Lake could be attributed to water leakage through the vertical tower of the aerator (Fast 1971a; Fast et al. 1973). Intensive investigation of long-term responses to aeration are necessary to clarify the role of nutrient limitation and internal loading reduction in regulation of algal productivity.

276. Experiments conducted at Mirror Lake demonstrated that hypolimnetic aeration can disrupt the vertical distribution of some blue-green algae. Before treatment, a dense population of Oscillatoria rubescens occupied a narrow zone at the interface between the metalimnion and the hypolimnion (Smith et al. 1975). Circulation currents produced by the aerator distributed the population throughout the hypolimnion; possibly accounting for increased phosphorus concentrations there.

277. The available research results illustrate conflicting responses of zooplankton to hypolimnetic aeration. For example, Fast (1971a) observed a large increase in the abundance of Daphnia pulex following aeration at Hemlock Lake. Other lakes exhibit little or no change in zooplankton abundance in response to treatment (Linder and

Mercier 1954; Confer et al. 1974; Fast et al. 1975b). Mean zooplankton abundance in Spruce Knob Lake during the aeration period (July, 1974 - October, 1976) declined relative to the pre-aeration condition (July, 1973 - July, 1974) (Hess 1977). The effect of including two winters in the aeration period as compared with only one in the "control" year is unknown (Hess 1977). (Actually, the aeration results may have covered only July, 1974 - October, 1975; the exact dates are open to question because of discrepancies in the text of Hess (1977).)

278. During aeration of Hemlock Lake, Daphnia pulex invaded the lake and became a dominant member of the zooplankton community (Fast 1971a). Before aeration, all zooplankton were restricted to shallow water (< 11 m) above the zone where oxygen was depleted (Fast 1971a, b). Without a daytime refuge in an oxygenated hypolimnion, the large D. pulex were probably excluded from the lake by intense fish predation in the epilimnion, and smaller herbivores dominated the community. Following treatment, the small-bodied cladocerans Bosmina and Diaphanasoma increased to a lesser extent than Daphnia, and the Diaptomus copepod population remained essentially the same. A combination of competitive pressure from D. pulex and predation by a more abundant Chaoborus population may have prevented more dramatic responses in small herbivorous species. These insect larvae remove as much as 30 percent of the standing stock of "preferred" prey species, primarily small- to medium-sized food items (Pastorok 1980).

279. The Hemlock Lake experiment provides support for the hypothesis that hypolimnetic aeration reduces the intensity of predator-prey interactions between fish and zooplankton by expansion of habitat and provision of a refuge for prey (see above theoretical discussion). Presumably, D. pulex underwent a typical diel migration after treatment, remaining in the hypolimnion during the day to avoid fish predation and moving up at night to graze on phytoplankton in the epilimnion. Nevertheless, technical problems during the experiments weaken the results considerably and preclude generalization.

280. During treatment of Spruce Knob Lake, mean zooplankton abundance was 45 percent less than it was before aeration (Hess 1977). The crustacean zooplankton, which consisted of Diaptomus pallidus, Daphnia ambigua, cyclopoid copepods, Bosmina longirostris, and Diaphanasoma leuchtenbergianum, accounted for 17 percent of the

zooplankton during the pre-aeration study, but only 3 percent during the treatment period. Bosmina was dominant among the cladocerans; its production seemed to be unaffected by aeration. Kellicottia bostoniensis, a dominant rotifer, exhibited lower production and lower mean abundance during the treatment period; moreover, population fluctuations were more extreme than they were during the "control" study.

281. Unfortunately, there was no clear relationship between hypolimnetic aeration and changes observed in the zooplankton community at Spruce Knob Lake. Although primary production remained the same throughout all study years, chlorophyll was low during the 1975 treatment (LaBaugh 1979, 1980). A decline in food availability induced by natural destratification during June, 1975, may partly account for zooplankton responses in Spruce Knob Lake.

282. In Tory Lake, hypolimnetic aeration failed to provide Daphnia pulex with a bottom-water refuge from fish predation. During summer, dominance in the zooplankton community shifted from Daphnia pulex and the large predatory cyclopoid Mesocyclops edax to the herbivorous calanoid Diaptomus oregonensis, several smaller cladocerans, and rotifers.* Size-selective predation by the minnow Pimphales promelas probably was responsible for the change in community composition. Since the oxygen-deficient (and possibly toxic) metalimnion acted as a barrier to fish and zooplankton movements, hypolimnetic aeration failed to expand predator-prey habitat. Thus, the intensity of predation pressure on large zooplankton may have been unaffected by treatment at Tory Lake.

283. Benthic macroinvertebrates. Changes in the benthic fauna of Hemlock Lake during hypolimnetic aeration illustrate the expected outcomes. However, it should be emphasized that the water column remained stratified for only 10 weeks during treatment. Compared to the previous control year, total numbers of benthic macroorganisms almost doubled,while biomass declined slightly during treatment (Fast 1971a). Chironomids accounted for a large portion of the response.

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Oligochaetes also exhibited some increase in abundance. Mayflies and odonates, on the other hand, showed little response to treatment, perhaps because of their longer generation times and residence of critical stages in littoral habitat. Although Chaoborus spp. increased in number by 250 percent, their biomass fell by 22 percent, probably because of a predation-induced shift toward a smaller species. Predation by rainbow trout undoubtedly increased in bottom waters after treatment, and selective removal of large Chaoborus could explain the shift from C. flavicans to C. punctipennis. The results of Stenson (1978) and von Ende (1979) illustrate the importance of fish predation in controlling the distribution and abundance of Chaoborus species.

284. Finally, aeration modified the depth distributions of chironomids and Chaoborus in Hemlock Lake. These major components of the benthos shifted their distributions towards the profundal zone, especially during late summer.

285. Hess (1977) concluded that hypolimnetic aeration of Spruce Knob Lake had little effect on benthic macroinvertebrates. Chaoborus punctipennis dominated the benthic assemblage throughout the study. Chironomid larvae and pupae were subdominant, while oligochaetes, ostracods, nematodes, and molluscs were also represented. Analysis of Variance indicated no significant differences in total benthos between the two sampling stations for either pre-aeration or aeration studies (Hess 1977). The text of Hess (1977) is unclear regarding the tests of spatial distribution for Chaoborus. Also, Hess (1977) gives no statistical comparisons of benthos abundance during pre-aeration and aeration periods. Indirect observations at one station indicated that chironomids were more abundant during aeration than before treatment (R. Ochalek, personal communication, in Hess 1977).

286. Adult crayfish abundance showed little response to hypolimnetic aeration in Spruce Knob Lake (Hess 1977). Crayfish were restricted to the epilimnion throughout the study. Habitat expansion did occur in the summer following aeration, but it was probably related to sediment composition and food availability rather than oxygen levels. Although males normally dominate shallow-water crayfish populations, the sex ratio was nearly even in all areas during 1974 and skewed toward females in shallow areas during 1975. These results are similar to the findings of Fast and Momot (1973) at

Hemlock Lake; i.e., an atypical sex ratio in shallow water populations and little change in depth distribution during hypolimnetic aeration.

287. Fisheries. Although few studies have examined fish responses to hypolimnetic aeration, the available data generally show good survival of stocked trout and expansion of habitat for natural populations of coldwater fishes (e.g., Fast 1971a, 1973b; Hess 1977; Overholtz et al. 1977; Garrell et al. 1978). In north temperate lakes where epilimnetic temperatures in summer are favorable for salmonid growth and survival, trout are generally found throughout the water column during aeration. In southern reservoirs, coldwater species may be restricted to lower waters because of lethal temperatures near the lake surface.

288. After only 20 days of hypolimnetic aeration at Hemlock Lake, the depth distribution of rainbow trout expanded from the 0 - 6 m water layer to the entire water column (0 - 18 m) (Fast 1973b). During summer of the year before treatment, trout were restricted to the upper 10 m of the lake by anoxic conditions in the hypolimnion. Fast (1973b) suggested that gradual lowering of epilimnetic temperatures by water leakage from the aerator tower also made additional habitat available to trout. The large *Daphnia pulex*, which invaded the lake during the treatment year, were the most important trout food numerically while *Chaoborus* larvae were the second major component of the diet.

289. Hypolimnetic oxygenation of Ottoville Quarry by side-stream-pumping created suitable trout habitat in the hypolimnion during summer. After treatment most trout occupied depths below 4 m where temperatures were less than 20°C. Gizzard shad, on the other hand, preferred depths less than 5 m and temperatures greater than 12°C. Oxygen concentrations were adequate for survival of both fish species throughout the water column. During treatment, oxygen reached 16 - 20 mg/l (at 8 - 12°C) in the hypolimnion without apparent adverse effects on trout survival.

290. Hypolimnetic aeration of Lake Waccabuc resulted in successful growth of trout stocked directly into the hypolimnion (Garrell et al. 1978). Diet analysis suggested that fish were feeding primarily on *Chaoborus* and Chironomidae in the hypolimnion. The presence of some epilimnetic prey in fish stomachs indicated that stocked trout were migrating through the low-oxygen metalimnion.

Sonar traces showed trout were distributed throughout the lake; some fish must have migrated into shallower water after being stocked directly into the hypolimnion (Fast et al. 1975a).

291. In Spruce Knob Lake, rainbow trout were distributed deeper during July of the aeration years as compared with the pre-aeration period (Hess 1975, 1977; Figure 10). As the summer progressed, however, the aerator was unable to keep up with oxygen demand, and trout returned to predominately epilimnetic habitat. Throughout the study, trout generally avoided areas with less than 5 mg/l dissolved oxygen. Nevertheless, the anoxic metalimnion present during summer 1975 did not interfere with vertical movements of the fish. After examining the percentage of empty fish stomachs and the average weight of food per stomach, Hess (1977) concluded that trout fed more heavily during summer of aeration periods, when the fish had access to the entire water column. At least during the 1975 experiment, trout seemed to display greater selectivity toward larger food items such as fish, crayfish, and large terrestrial insects. Trout distribution and feeding habits resulted in better angler catches earlier in the season. Boat anglers were generally more successful than shore anglers, especially during 1975 when aeration influenced a small volume of water offshore.

292. Although hypolimnetic aeration/oxygenation may facilitate the development of two-story or three-story fisheries, especially in southern reservoirs, little data on actual experiences are available. As mentioned previously, some spatial segregation of warmwater and coldwater fishes was apparent after hypolimnetic oxygenation of Ottoville Quarry (Overholtz et al. 1977). In lakes where metalimnetic oxygen demand is high, hypolimnetic treatment will not prevent formation of a midwater oxygen depletion zone (Smith et al. 1975; Serns 1976; Garrell et al. 1978; Taggart and McQueen in press). A three-story fishery may be impossible under these conditions. The ability of fish to migrate through an anoxic layer may be a species-specific characteristic. Moreover, the effectiveness of a low oxygen barrier is probably related to the presence of concentrated toxic chemicals. Further research is needed to relate habitat availability to fish community structure during hypolimnetic aeration.

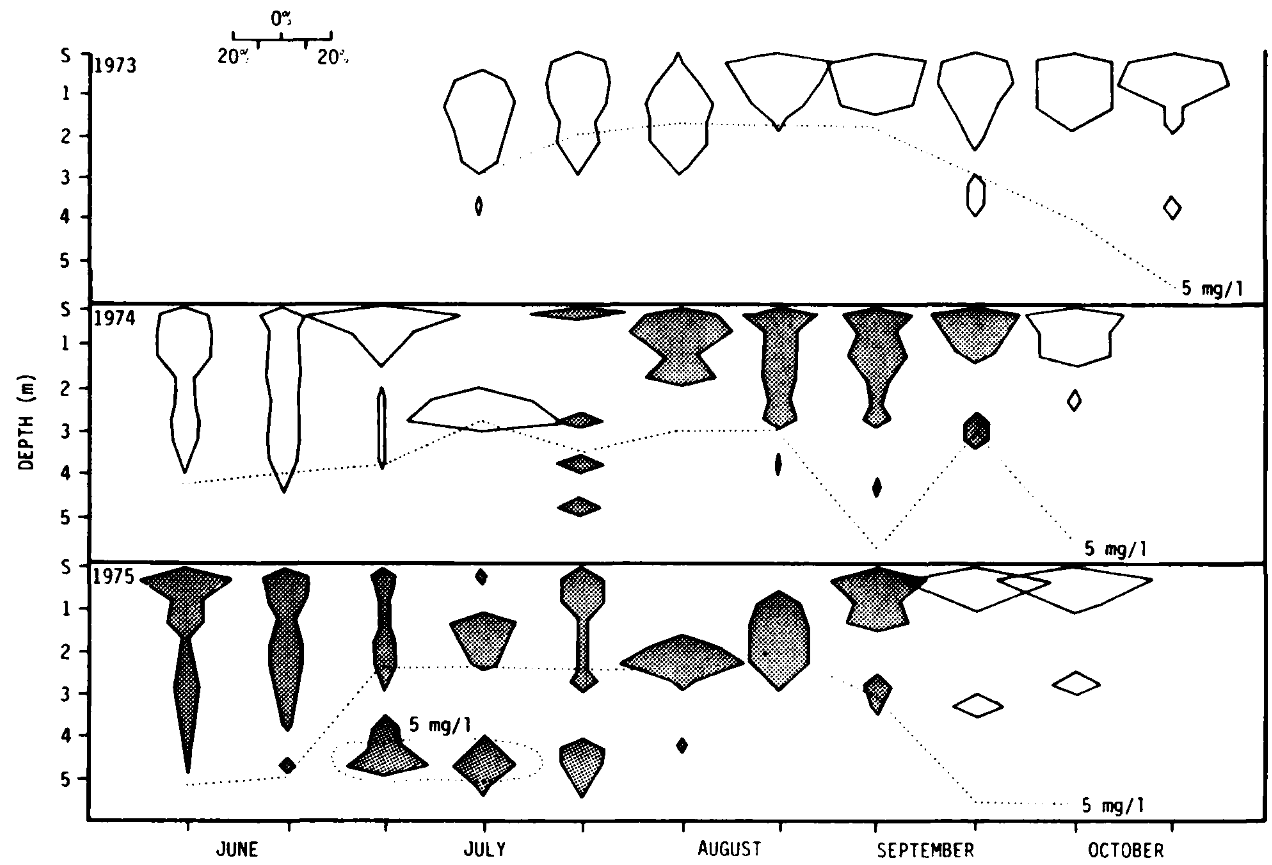

Figure 10. Summer vertical distributions of trout at Spruce Knob Reservoir. Open blocks = no aeration; shaded blocks = aeration; dotted line = 5 mg/1 oxygen level (after Hess 1977).

PART IV: AERATION OF RESERVOIR RELEASES

293. This chapter considers specialized applications of aeration techniques to reservoir discharges. The various techniques are broadly classified according to the location of aeration devices; i.e., aeration upstream of the dam, aeration in outlet works, and tailwater aeration. The emphasis of these sections is a brief description of techniques and summary of results since 1970. King (1970b) and Reaeration Research Program Management Team (1975) reviewed earlier research on reaeration of streams and reservoirs.

Upstream Aeration

Injection of oxygen or air

294. Diffused oxygen or air may be injected into the hypolimnion to raise DO content of reservoir discharges. The techniques considered in this section were not designed to partially or completely destratify the reservoir; localized mixing will be discussed later. Two general approaches have been taken: oxygen or air injection immediately upstream of the penstock intake and injection of a bubble plume into the withdrawal zone further upstream. Oxygenation is generally preferred to air injection, since the latter may adversely impact downstream fisheries by inducing nitrogen gas supersaturation (e.g., Speece 1975).

295. Speece and coworkers (e.g., Speece et al. 1973, 1976; Crate et al. 1978) have investigated the effects of hypolimnion oxygenation using an unconfined bubble plume in Clark Hill Reservoir. Equipment is designed to deliver bubbles which are sized for maximum absorption efficiency in a given height of rise (Figure 11). Compared to air injection, the reduced gas flow and high absorption efficiency during oxygen pumping minimize the risk of destratification; the bubbles are almost completely absorbed by the time they have risen to the metalimnion (Speece et al. 1973).

296. During September and October, 1975, Speece et al. (1976) tested several diffuser configurations at Clark Hill Reservoir and found that higher oxygenation efficiencies could be achieved by: (a) using diffusers capable of generating 2-mm-diameter bubbles as compared with those producing 4-5 mm bubbles, and (b) positioning of

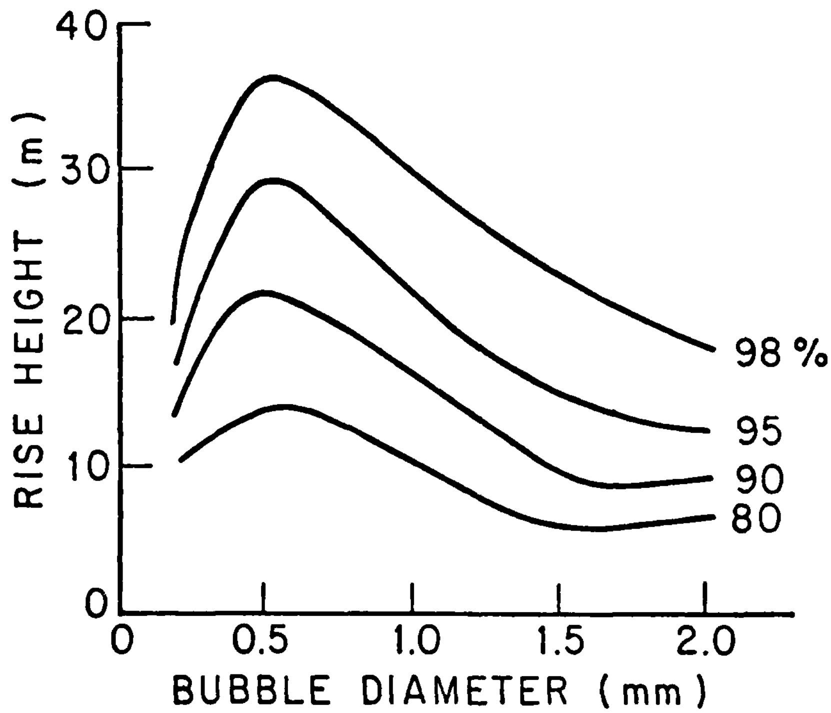

Figure 11. Rise height required to achieve indicated absorption efficiency vs. bubble diameter (from Speece et al. 1973).

the diffusers away from the penstock intake. With diffuser racks located about 120 ft away from the intake, the oxygen bubbles had a longer contact time (about 120 sec); and the bubble plume was not entrained in the penstock. At a turbine discharge rate of 2,940 cfs, injection of 51 tons/day oxygen produced a discharge DO of up to 8 mg/l with 85 $\pm$ 5 percent oxygen absorption efficiency. Background DO concentrations at this time were about 2 mg/l. During tests in 1976, hypolimnetic oxygen injection at distances of 300 ft in front of the dam still resulted in 100 percent withdrawal of absorbed oxygen with a pumping rate of 41-72 tons/day oxygen (Givler et al. 1977).

297. Evaluation of various diffusers showed that oxygen concentrations could be elevated more efficiently by using diffusers with 0.5 or 2.0 ft/min standard permeability instead of the 10 ft/min diffusers used in the 1975 and 1976 studies (Givler et al. 1977; Crate et al. 1978). Continuous injection of 100 tons/day of oxygen (2,000 lb/day per square foot diffuser area) for 8 days using 10 ft/min diffusers located one mile upstream from the dam resulted in 35 percent oxygen recovery in the discharge. Approximately 50 percent recovery was found during 30 days injection at 100 ton/day (500 lb/day per square foot diffuser) through diffusers having 2 ft/min standard permeability.

298. The lower oxygen recoveries during the later studies were at least partly due to less than complete overlap of the oxygenated water zone with the withdrawal layer (Caire et al. 1978). During the 1976 experiments, the bubble plume caused partial mixing of cold oxygen-enriched water with warmer epilimnetic water. The equilibrium level of the oxygen-enriched water was above the penstock withdrawal zone, resulting in only partial withdrawal of oxygenated water (Caire et al. 1978). Baffles or deflectors positioned above the diffusers have been used to dissipate plume energy and prevent excessive height of rise. When relative costs are considered, however, a line diffuser system perpendicular to the face of the dam is more effective than the rectangular array of rack diffusers used in the 1975-1976 studies (Caire et al. 1978; Smith 1980).

299. Overall, the oxygenation tests at Clark Hill Reservoir were successful at raising DO levels within the hypolimnion, in reservoir discharges, and in downstream areas. In a study of reservoir tailwaters, Dudley and Quintrell (1979) found that water

temperatures increased only slightly; DO concentrations rose more than 2 mg/l, up to levels of 4 - 6 mg/l during oxygenation, as compared with values during a control year (1978). Downstream populations of fish were similar during treatment and control periods, perhaps because impacts due to unaltered discharges were minimal. With oxygenation, fishes in general were caught further upstream.

300. Oxygenation techniques have also been applied at Fort Patrick Henry Reservoir (Ruane and Vigander 1973; Nicholas and Ruane 1975; Fain 1978). Oxygen transfer efficiency decreased from about 85 percent to about 50 percent as flux rates increased over the range 0.01 to 0.12 actual cubic feet per minute per square foot (ACFM/ft^2) through 15 - 20 m pore diffusers (Nicholas and Ruane 1975). Transfer efficiency was defined as the increase in mass flow rate of DO in the tailrace divided by mass rate of oxygen gas injection. Location of the diffusers did not affect transfer efficiency when the latter was above 60 percent. At oxygen flux rates of about 0.05 - 0.15 ACFM/ft^2 smaller-pore (1.5 - 2.0 m) diffusers had higher transfer efficiencies. When the diffusers were located 20 ft from the turbine intake, transfer efficiency increased with turbine discharge until a maximum efficiency value was reached. Fain (1978) presents a detailed summary of the oxygenation tests and cost estimates for a prototype system.

301. At Table Rock Dam, DO concentrations in the discharges were only 2 - 4 mg/l during September - December, 1970 (USAE 1972; Proctor 1973). Although spillway releases elevated DO concentrations, they also produced higher temperatures downstream while requiring power cuts. As a more practical solution, air was injected at approximately 2,100 cfm through diffusers located 50 ft, 100 ft, or 500 ft upstream of the penstock intakes. The results indicated that artificial elevation of DO concentrations in releases declined as the diffusers were placed further from the intakes. When turbine vents were open, however, maximum DO concentration (4 mg/l at a downstream station) were obtained with the diffusers at the 100-ft location. Diffusers were not as effective as penstock air injection. Drain-line injection without the turbine air vents open resulted in 4.2 mg/l. For maximum efficiency, air should be injected as far upstream in the penstock as possible (Proctor 1973).

302. Essentially any system capable of hypolimnetic aeration/oxygenation may be used to raise DO levels in releases from low-level withdrawal. For example, Speece et al. (1973) have recommended locating a Downflow-Bubble-Contact Aerator near a dam outlet for oxygenation of waters in the withdrawal zone. Other special devices including the U-tube hypolimnetic aerator are described by Leach (1974).

Localized mixing

303. Aeration of reservoir releases may be accomplished by localized destratification just upstream from the dam. This approach has been used in Eufaula Reservoir (Leach 1970, Leach et al. 1970) Okatibbee Lake (Dortch and Wilhelms 1978), and Allatoona Reservoir (USAE 1973).

304. Diffused air was injected near the bottom of Eufaula Reservoir at a point 229 m upstream from the dam. Dissolved oxygen concentrations in reservoir discharges increased from 3.0 mg/l immediately before aeration to 4.0 - 5.5 mg/l, with greater oxygen levels being obtained at higher discharge rates (Leach 1970; Leach et al. 1970). For any discharge rate, dissolved oxygen content of the released water increased over the course of the 1.5-month aeration study in 1968. Near the dam, isopleths of dissolved oxygen were lowered by power releases under normal operating conditions, but aeration further suppressed the DO strata. Changes in oxygen levels within the reservoir were noted, but upstream effects were less than expected because most aerated water was being withdrawn through the outlet works. Calculations suggested that 69 percent of the oxygen pumped into the reservoir was incorporated into discharge water.

305. Dissolved oxygen concentrations in releases from Allatoona Reservoir were also elevated by diffused air mixing near the dam (USAE 1973). DO content of peak flow generation releases exceeded 4 mg/l during treatment, except for July and August 1968. Low flow generation releases contained more than 4 mg/l DO except for about 1 week in late August. The temperature of discharged water was increased about 2 - 4°C during the June - August period for both treatment years.

306. Dortch and Wilhelms (1978) found that localized mixing with a Garton pump was an effective and economical means of improving the water quality of low flow releases from Okatibbee Reservoir.

Using a 1.83-m-diameter propeller suspended about 1 m below the surface, water was pumped downward at approximately 1.7 m^3/sec. Oxygenated water from the epilimnion was thus mixed with hypolimnetic water, and an approximate 50:50 mixture was withdrawn by low-level intakes. Without localized mixing, anoxic hypolimnetic water was reaerated within the outlet works to about 5.9 mg/l DO. After only 15 min of pump operation, the temperature and DO of the discharge water increased by 3.6° C and 1.0 mg/l with a constant discharge rate of 1.4 m^3/sec. Profiles of temperature and DO at a station 10 - 30 m upstream of the pump showed no effect of mixing in the reservoir itself.

Aeration in Outlet Works

Normal operation

307. The Bureau of Reclamation and the USAE have conducted research on reaeration capabilities in hydraulic structures. Perhaps the simplest operational approach to raising DO concentrations in discharges is to release some water over the spillway. After water is aerated by turbulent flow, it plunges into the stilling basin and entrained air is forced into solution. Johnson and King (1975) and Wilhelms (1975) discuss models for prediction of changes in DO concentration based on temperature characteristics of the stilling basin and spillway, and initial DO levels in the reservoir and stilling basin. Although spillway releases may be successful at elevating downstream DO concentrations, they are not a practical long-term solution. Spillway releases may produce high temperatures in downstream areas; they require loss of power generation capacity; and they are impossible during low pool (USAE 1972). In addition, spillway releases can cause gas supersaturation and fishkills (Ebel and Raymond 1975), although spillway redesign may solve this problem (Smith 1974).

308. Reaeration normally occurs during travel of water through outlet works. For example, anoxic water was reaerated at the outlet at Okatibbee Dam even without localized mixing, providing up to 5.9 mg/l DO (Dortch and Wilhelms 1978). The Bureau of Reclamation found that in most cases the combined effects of control devices, conveyance structures, and energy dissipators eliminated DO deficiencies and

raised oxygen levels up to 90 percent saturation or more (Reaeration Research Program Management Team 1975). From tests conducted at Beltzville Dam, Hart and Wilhelms (1977) obtained similar results and concluded that most reaeration in the outlet works was induced by "shallow, turbulent and supercritical flow in the water-quality conduit downstream of the control gate." Also, the numerical model SELECT developed by the U.S. Army Engineer Waterways Experiment Station (WES) successfully predicted concentrations of conservative water-quality parameters in reservoir releases.

309. Design of hydraulic structures to optimize reaeration capabilities has been the subject of a number of studies. Harshbarger et al. (1975) examined reaeration in models and prototypes of low-level gated discharge tunnels equipped with air vents. Others have modeled reaeration through turbine draft tubes and air vents (e.g., Cassidy 1973; Raney 1975; Quigley et al. 1975; Quigley and Boyle 1976). Quigley et al. (1975; Quigley and Boyle 1976) obtained DO increases of up to 4.1 mg/l during vented draft tube aeration (8-in. Kaplan hydroturbine), accompanied by slight reduction in potential peak power but no loss of operating power. Simulation models of draft tube ventilation suggested aeration efficiencies of up to 50 percent, but as much as a 50 percent drop in total efficiency of power production (Cassidy 1973). In field tests conducted at Table Rock Dam, turbine air vents resulted in significant elevation of discharge DO concentrations at midrange generation rates (USAE 1972; Proctor 1973).

Artificial aeration

310. Reaeration of reservoir discharges has also been accomplished by air or oxygen injection at various points in the outlet works; e.g., in penstocks or in turbine vents (e.g., USAE 1972; Proctor 1973). Although these methods can be more effective at raising DO concentrations than upstream aeration, some problems may arise in practice. For example, air or oxygen bubbles injected into penstocks will move upstream due to buoyancy except at large discharge rates. Injection into turbines may cause rough running and power loss. On the other hand, the Table Rock tests indicated that air inputs of up to 8,000 cfm per generator did not significantly reduce power generation efficiency (Proctor 1973).

Tailwater Aeration

311. Various techniques are available for instream aeration, including diffusers, mechanical aerators, weirs and cascades, and U-tubes. However, Ruane and Vigander (1973) found that hypolimnetic oxygenation of Fort Patrick Henry Reservoir required less initial capital investment than air injection in the tailrace. A complete review of downstream aeration is beyond the scope of this report. Previous reviews include those by King (1970b) and Toetz et al. (1972).

PART V: AERATION/CIRCULATION FOR USAE RESERVOIRS

312. The following sections briefly summarize limnological characteristics of USAE reservoirs, including morphometry, water quality, and fisheries resources. In addition, a general procedure for evaluation of aeration techniques is developed for use in reservoir management.

Characteristics of USAE Reservoirs

Summary of EPA/NES data

313. The National Eutrophication Survey (NES) was conducted from 1972 to 1975 by the U.S. Environmental Protection Agency (EPA) to evaluate eutrophication problems in the nation's lakes and reservoirs. Development of data on nutrient sources, nutrient inputs, and water quality parameters involved surveys at over 800 lakes and reservoirs, 4,200 tributaries, and 1,000 sewage treatment plants. For details of methods used in data collection and compilation, refer to U.S. EPA (1974, 1975). Allum et al. (1977) offer a critical evaluation of the EPA/NES data.

314. The NES Program included 107 reservoirs managed by the U.S. Army Corps of Engineers (Table 16). The purpose of this section is to briefly summarize the pertinent morphometric and water quality characteristics of these reservoirs. Basic statistics for USAE reservoirs will also be compared with characteristics of artificially mixed lakes and reservoirs.

315. The uneven geographical distribution of these reservoirs is evident from a consideration of USAE Districts and Divisions in which the reservoirs are located (Table 17). Most of the reservoirs sampled during the NES program are located in the south-central U.S. Physical and chemical parameters for 187 USAE reservoirs were given by Leidy and Jenkins (1977). The majority of reservoirs included in their report were also in the central U.S. A comprehensive summary of water quality characteristics and morphometry of over 300 USAE reservoirs is now being prepared.*

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* Personal communication, W.W. Walker, Jr., September, 1980, 1127 Lowell Road, Concord, Massachusetts.

TABLE 16. USAE RESERVOIRS IN EPA/NES COMPENDIUM
(Compiled by W.W. Walker, Jr.)

STORET NO.	RESERVOIR NAME	STORET NO.	RESERVOIR NAME
0101	BANKHEAD LAKE	3107	PAWNEE RESERVOIR
0105	HOLT LOCK AND DAM	3503	CONCHAS RESERVOIR
0501	BEAVER RESERVOIR	3641	ALLEGHENY RESERVOIR
0503	BLUE MOUNTAIN LAKE	3801	LAKE ASHTABULA
0504	BULL SHOALS RESERVOIR	3812	LAKE SAKAKAWEA
0507	DEGRAY RESERVOIR	3901	BEACH CITY RESERVOIR
0511	MILLWOOD RESERVOIR	3905	CHARLES MILL RESERVOIR
0512	NIMROD LAKE	3906	DEER CREEK RESERVOIR
0513	NORFOLK LAKE	3907	DELAWARE RESERVOIR
0514	OUACHITA LAKE	3908	DILLON RESERVOIR
0515	TABLE ROCK RESERVOIR	3921	MOSQUITO CREEK RESERVOIR
0516	GREER'S FERRY RESERVOIR	3924	PLEASANT HILL RESERVOIR
0606	DON PEDRO RESERVOIR	3928	ATWOOD RESERVOIR
0616	LAKE MENDOCINO	3929	BERLIN RESERVOIR
0620	SANTA MARGARITA LAKE	3934	TAPPAN RESERVOIR
0804	CHERRY CREEK LAKE	4004	LAKE EUFAULA
1301	ALLATOONA RES.	4006	FORT SUPPLY RESERVOIR
1304	CLARK HILL RESERVOIR	4011	KEYSTONE RESERVOIR
1310	SIDNEY LANIER LAKE	4012	OOLOGAH RESERVOIR
1604	DWORSHAK RESERVOIR	4013	TENKILLER FERRY RES.
1706	CARLYLE RESERVOIR	4015	WISTER RESERVOIR
1735	REND LAKE	4104	HILLS CREEK RESERVOIR
1739	SHELBYVILLE RESERVOIR	4201	BLANCHARD RESERVOIR
1827	MISSISSINEWA RESERVOIR	4216	SHENANGO RIVER RESERVOIR
1828	MONROE RESERVOIR	4220	BELTZVILLE LAKE
1909	RATHBUN RESERVOIR	4228	STILLWATER LAKE
1910	RED ROCK RESERVOIR	4505	LAKE HARTWELL
2002	COUNCIL GROVE RESERVOIR	4701	BARKLEY LAKE
2003	ELK CITY RESERVOIR	4706	CHEATHAM RESERVOIR
2004	FALL RIVER RESERVOIR	4720	OLD HICKORY RESERVOIR
2005	JOHN REDMOND RESERVOIR	4723	J. PERCY PRIEST RES.
2006	KANOPOLIS RESERVOIR	4803	BELTON RESERVOIR
2007	MARION RESERVOIR	4807	CADDO LAKE
2008	MELVERN RESERVOIR	4809	CANYON RESERVOIR
2009	MILFORD RESERVOIR	4815	LAKE LEWISVILLE
2011	PERRY RESERVOIR	4816	LAKE KEMP
2012	POMONA RESERVOIR	4818	LAKE O' THE PINES
2013	TORONTO RESERVOIR	4819	LAKE LAVON
2014	TUTTLE CREEK RESERVOIR	4826	O. C. FISHER
2015	WILSON RESERVOIR	4827	SAM RAYBURN RESERVOIR
2101	CUMBERLAND LAKE	4829	SOMERVILLE LAKE
2102	DALE HOLLOW RESERVOIR	4831	STILLHOUSE HOLLOW RESERV
2105	BARREN RIVER RESERVOIR	4833	WRIGHT PATMAN
2737	GULL LAKE (SOUTH BASIN)	4834	LAKE TEXOMA
2746	LEECH LAKE	4839	WHITNEY RESERVOIR
2801	ARKABUTLA RESERVOIR	5011	WATERBURY RESERVOIR
2802	ENID LAKE	5105	JOHN W FLANNAGAN RES.
2805	SARDIS LAKE	5106	JOHN H KERR RES.
2806	GRENADA LAKE	5401	BLUESTONE RESERVOIR
2901	CLEARWATER LAKE	5403	SUMMERSVILLE RESERVOIR
2902	POMME DE TERRE RESERVOIR	5404	TYGART RESERVOIR
2903	STOCKTON RESERVOIR		
2906	LAKE WAPPAPELLO		
3006	KOOCANUSA RESERVOIR		
3101	BRANCHED OAK RESERVOIR		
3102	HARLAN COUNTY RESERVOIR		

TABLE 17. GEOGRAPHICAL DISTRIBUTION OF USAE RESERVOIRS IN EPA/NES COMPENDIUM

District	Number of Reservoirs	Division	Number of Reservoirs
New York	1		
Philadelphia	1		
Baltimore	2	N. Atlantic	4
Wilmington	1		
Savannah	2		
Mobile	4	S. Atlantic	7
Rock Island	1		
St. Paul	3	N. Central	4
Pittsburgh	5		
Huntington	11		
Louisville	3		
Nashville	6	Ohio River	25
St. Louis	3		
Memphis	1		
Vicksburg	6		
New Orleans	3	Lower Miss. Valley	13
Little Rock	8		
Tulsa	15		
Fort Worth	9		
Albuquerque	1	Southwest	33
Kansas City	11		
Omaha	4	Missouri River	15
Walla Walla	1		
Seattle	1		
Portland	1	N. Pacific	3
Sacramento	1		
San Francisco	2	S. Pacific	3

316. The reservoirs in the EPA/NES compendium represent a wide variety of basin types and trophic states. Means and ranges for morphometric characteristics and water quality parameters are given in Table 18. Frequency distributions of parameter values are shown for surface area, mean depth, volume, water retention time, summer Secchi disc, mean summer chlorophyll a, alpha (extinction coefficient of water due to nonalgal factors), phosphorus loading per unit surface area, median total phosphorus, and median total nitrogen (Figures 12 through 21). Lake Sakakawea is largest in volume (28,200 x 10^6 m^3) and surface area (1,490 km^2), with a moderate mean depth (18.9 m). Stillwater Lake is the smallest in volume (1.41 x 10^6 m^3), surface area (1.41 km^2), and mean depth (1 m). Elk City Reservoir had the lowest median orthophosphate (0.003 mg/l), the lowest Secchi disc (0.2 m), and the highest alpha (7.98 m^{-1}). Charles Mill Reservoir had the highest chlorophyll level (67.1 μg/l), and Tygart Reservoir the lowest (1.2 μg/l).

317. Relationships between pairs of parameters were investigated using the product-moment correlation coefficient (Table 19). Many variables are correlated with mean depth or nutrient levels, but few are linearly related to surface area and volume. As expected, there is a high inverse correlation between Secchi disc and alpha. The lack of a relationship between chlorophyll a and total phosphorus or surface area loading indicates possible light limitation of algal growth in many of these reservoirs. This hypothesis is supported by the high alpha values (Figure 18) and low Secchi values (Figure 16) in some reservoirs. Moreover, nonalgal turbidity increases with total phosphorus (Figure 22); light limitation at higher total phosphorus values would obviate a relationship between chlorophyll and total phosphorus.

318. It is likely that many of these variables are related in a nonlinear fashion, explaining the relatively low linear correlation coefficients in Table 19. For example, there is an apparent nonlinear relationship between Secchi disc and total phosphorus (Figure 23). As mean depth increases, one expects the Secchi disc to increase at first, but eventually it should reach some maximum limit determined by light attenuation properties of water itself (e.g., Figure 24). Also, alpha is related to mean depth in a nonlinear manner (Figure 25).

TABLE 18. CHARACTERISTICS OF USAE RESERVOIRS AND ARTIFICIALLY MIXED RESERVOIRS

Parameter	USAE Reservoirs[a] Mean	USAE Reservoirs[a] Range	Mixed Reservoirs[b] Mean	Mixed Reservoirs[b] Range
Surface Area (km^2)	84.9	1.4-1,490	14.5	0.001-415
Mean Depth (m)	9.6	1.0-55.5	8.4	2.0-26.8
Volume (10^6 m^3)	1,064	1.4-28,200	131	0.002-3,454
Retention Time (days)	329	3-4,015		
Summer Secchi (m)	1.3	0.2-4.3		
Summer Chl a (μg/l)	11.6	1.2-67.1		
Alpha (m^{-1})	1.7	0.27-7.98		
P Loading (g m^{-2} yr^{-1})	4.6	0.04-105		
Total P (mg/l)	0.057	0.006-0.508[c]		
Ortho P (mg/l)	0.018	0.003-0.170[c]		
Total N (mg/l)	0.93	0-3.46[c]		
Inorganic N (mg/l)	0.50	0.04-3.29[c]		
No. Reservoirs	107		41	

[a] Data from EPA/NES compendium.

[b] Data from Table 4 for diffused-air mixing system (excluding Starodworski Lake; see text under "Review of Mixing Experiences" for explanation).

[c] Range of median values from three sampling dates during summer.

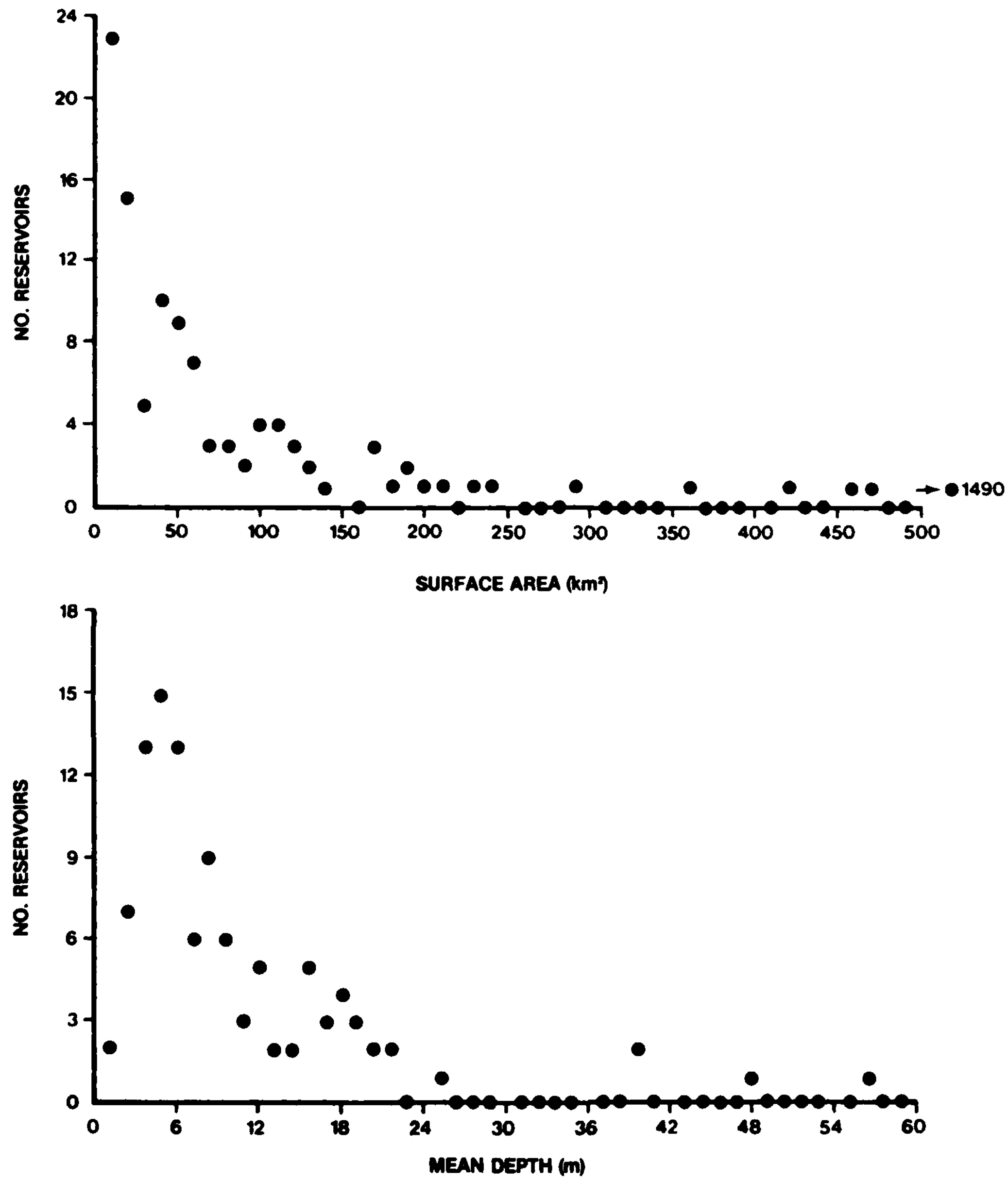


Figure 12. Frequency distribution of USAE reservoirs by surface area (km^2).
Figure 13. Frequency distribution of USAE reservoirs by mean depth (m).

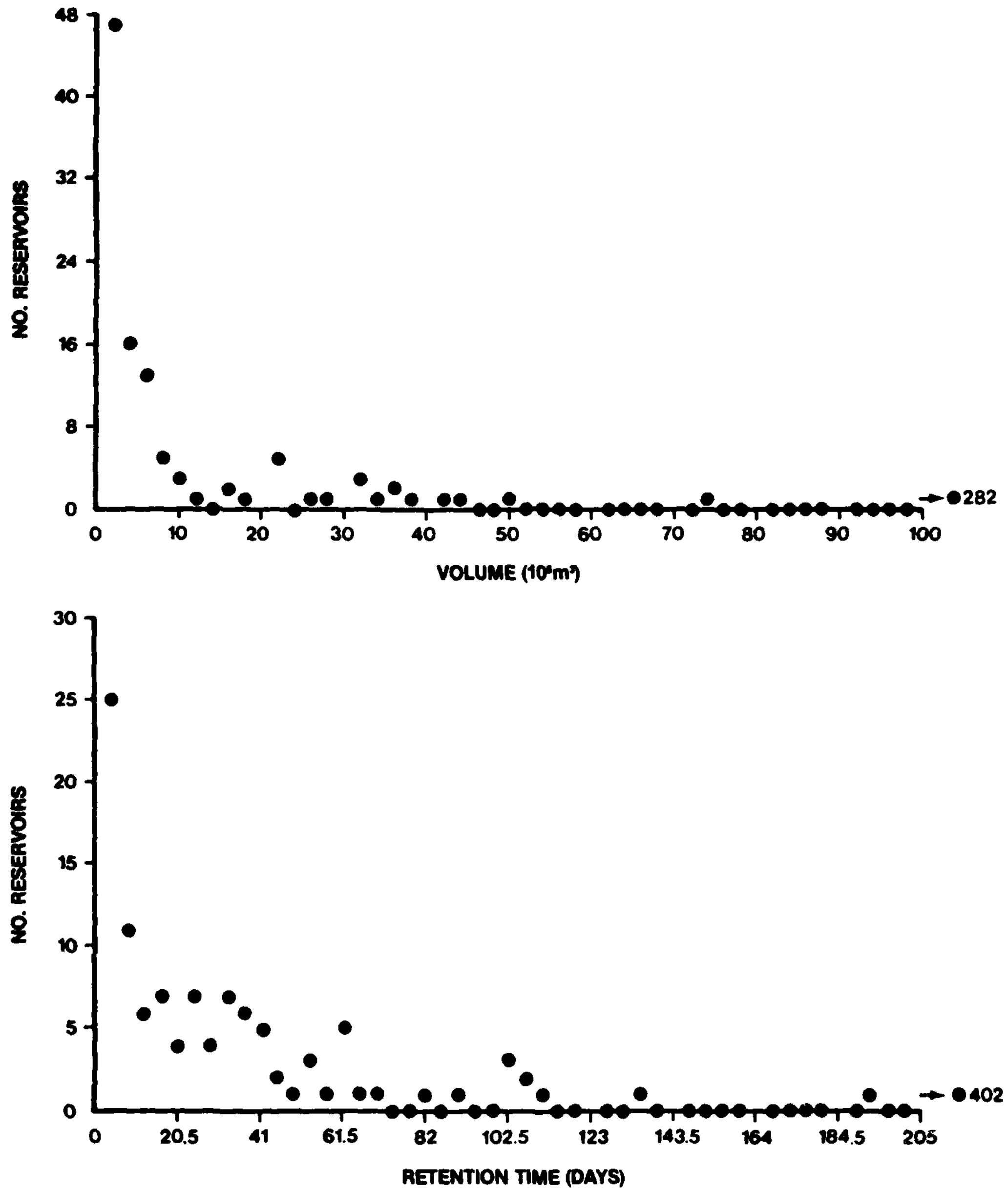


Figure 14. Frequency distribution of USAE reservoirs by volume (10^6 m^3).

Figure 15. Frequency distribution of USAE reservoirs by retention time (days).

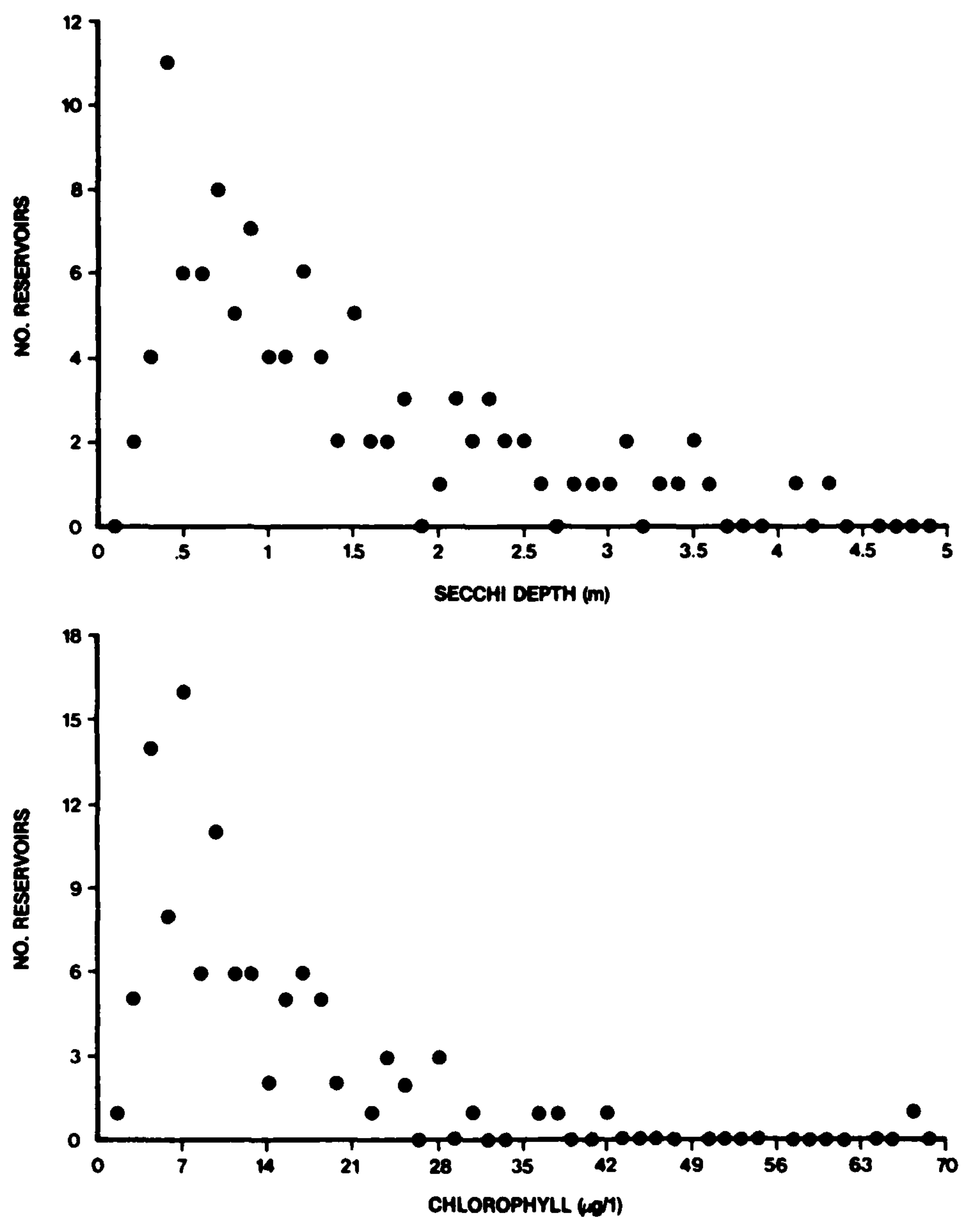
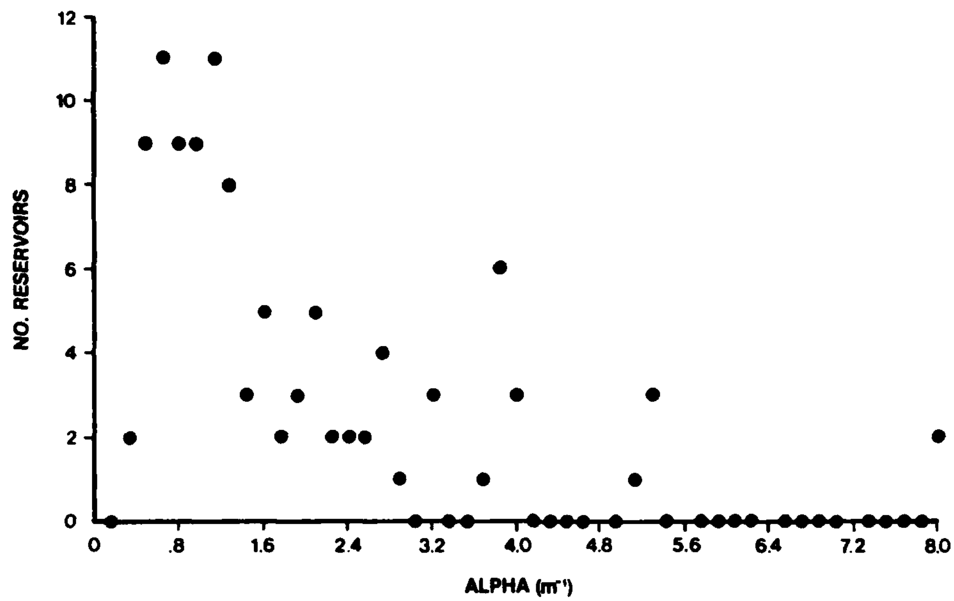


Figure 16. Frequency distribution of USAE reservoirs by Secchi disc value (m).

Figure 17. Frequency distribution of USAE reservoirs by chlorophyll a (µg/l).



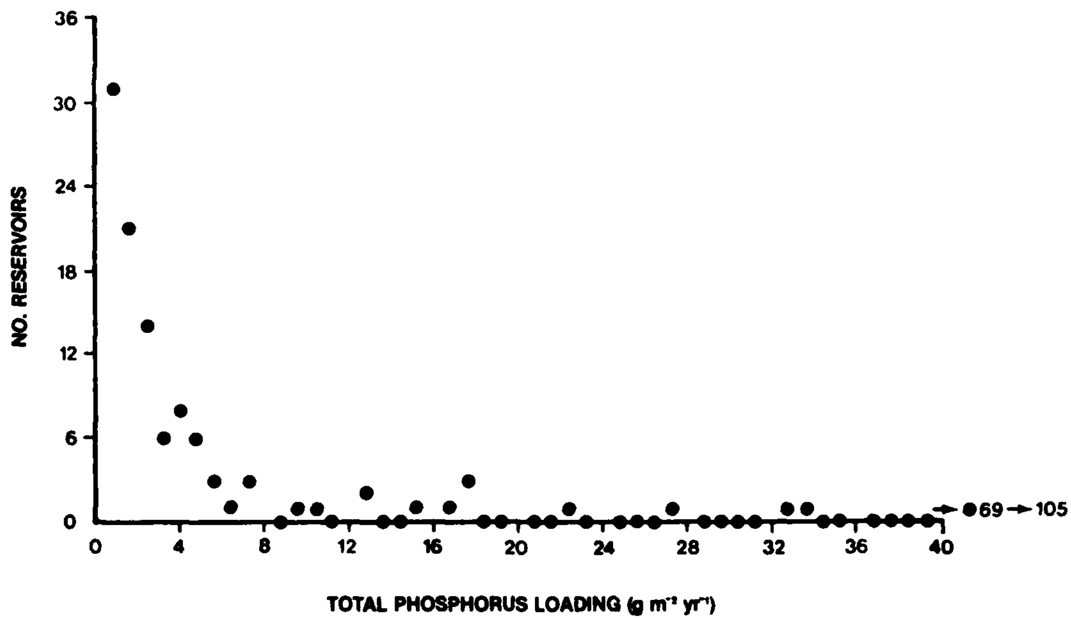


Figure 18. Frequency distribution of USAE reservoirs by alpha (m^{-1}).

Figure 19. Frequency distribution of USAE reservoirs by phosphorus loading ($g\ m^{-2}\ yr^{-1}$).

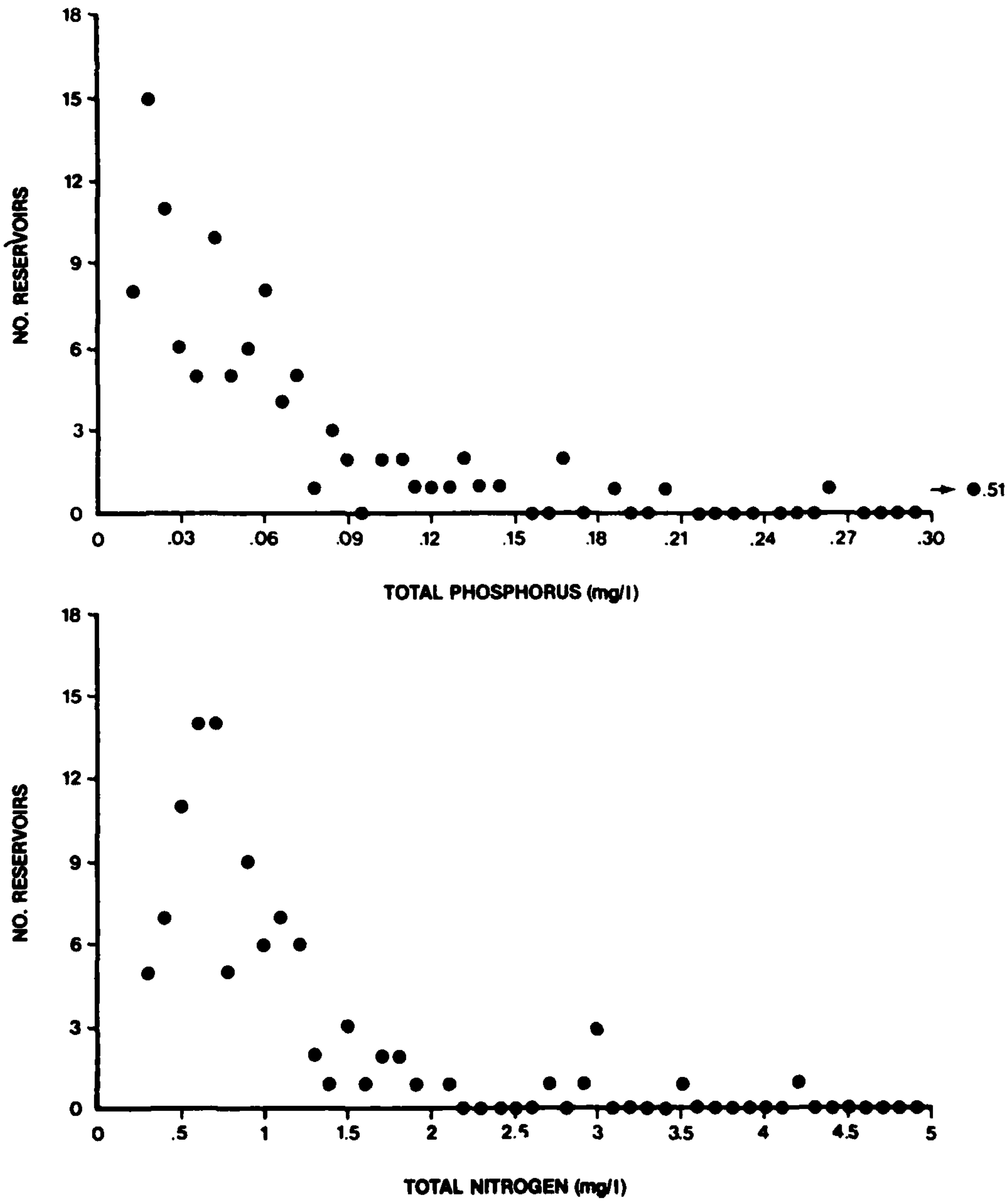


Figure 20. Frequency distribution of USAE reservoirs by total phosphorus (mg/l).
Figure 21. Frequency distribution of USAE reservoirs by total nitrogen (mg/l).

TABLE 19. CORRELATION MATRIX FOR USAE RESERVOIR CHARACTERISTICS[a]

	Surface Area	Mean Depth	Volume	Retention Time	Total P	Ortho P	Secchi disc	Chl *a*	P Loading	Alpha (α)	Inorganic N	Response time	Total N
Surface Area	1	.17	.92	.12	-.13	-.05	.18	-.16	-.07	-.15	-.17	.02	-.22
Mean Depth		1	.37	.08	-.31	-.16	.64	-.42	-.18	-.40	-.26	.09	-.37
Volume			1	.09	-.15	-.08	.30	-.19	-.07	-.19	-.16	.01	-.22
Retention time				1	-.12	-.15	.11	.05	-.25	-.13	-.27	.88	-.21
Total P					1	.56	-.48	.32	.33	.42	.23	-.03	.36
Ortho P						1	-.30	.29	.44	.24	.27	-.08	.37
Secchi disc							1	-.42	-.25	-.70	-.29	.07	-.43
Chl *a*								1	.09	.07	.07	.08	.35
P Loading									1	.19	.50	-.19	.51
Alpha (α)										1	.30	-.06	.34
Inorganic N											1	-.19	.93
Response time												1	-.14
Total N													1

[a] Underlined values are significant at $P<.01$

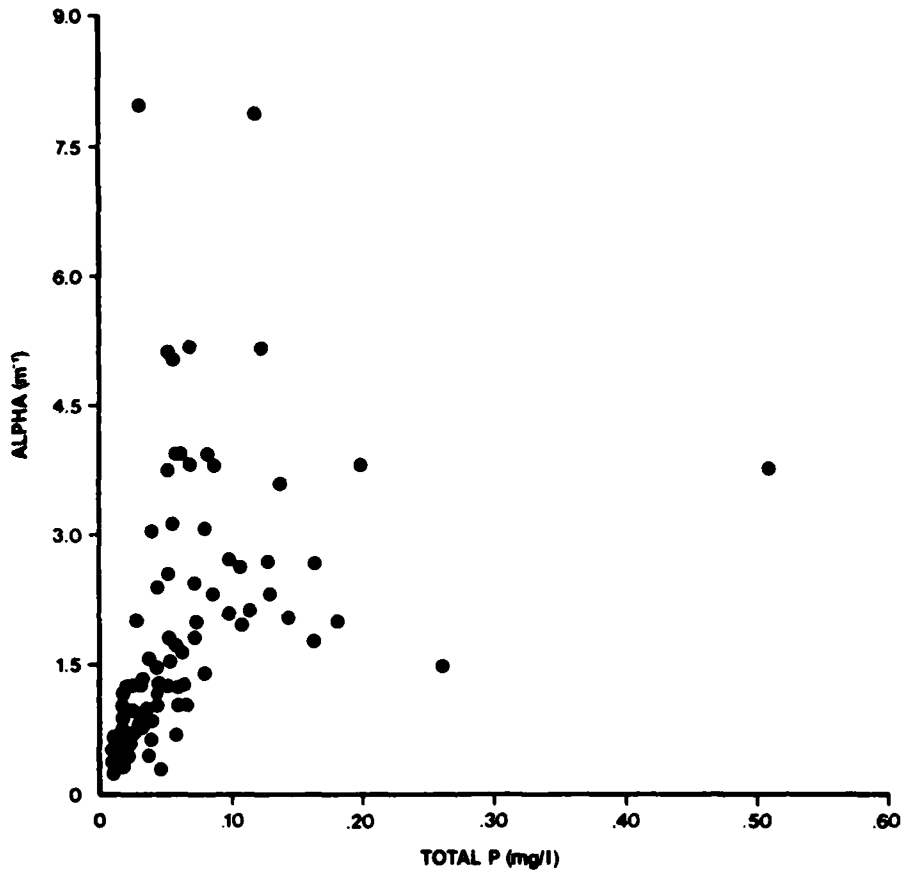


Figure 22. Non-algal turbidity (alpha) vs. total phosphorus in USAE reservoirs (EPA/NES data).

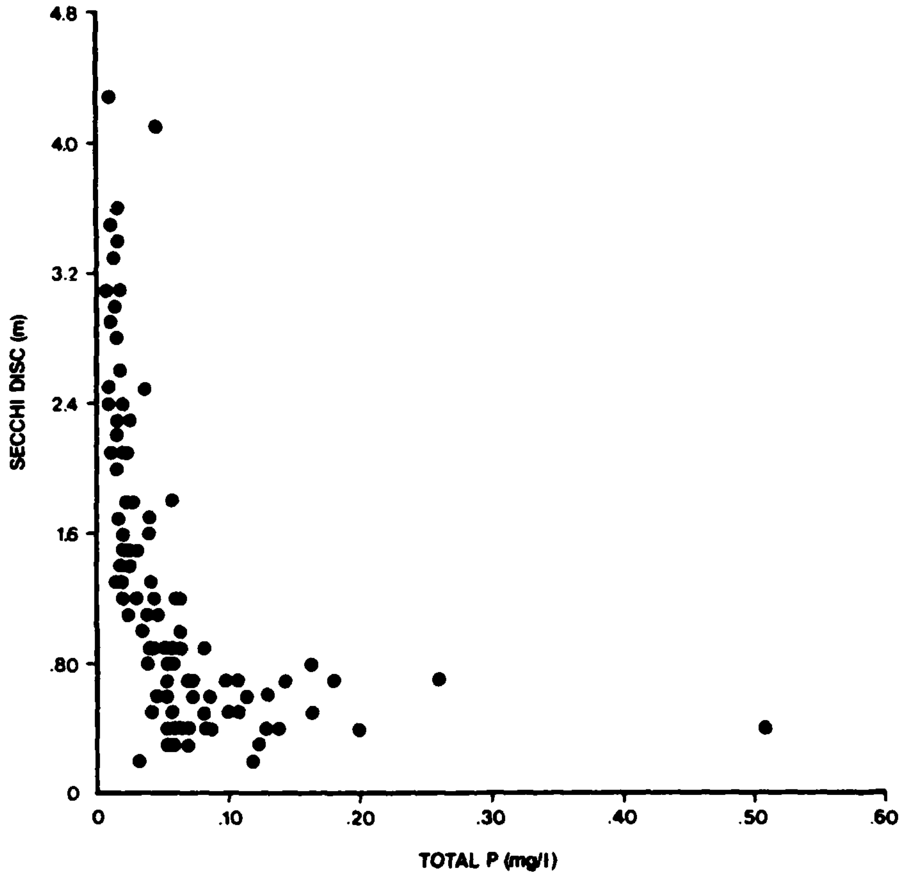


Figure 23. Secchi disc vs. total phosphorus in USAE reservoirs (EPA/NES data).

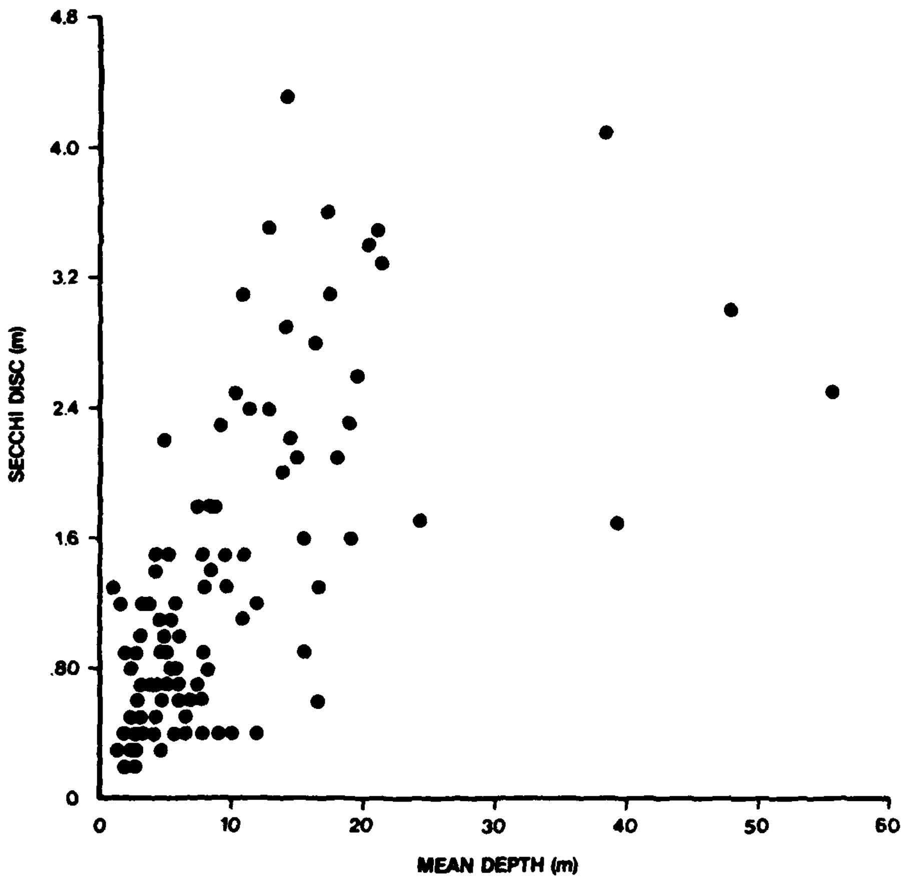


Figure 24. Secchi disc vs. mean depth in USAE reservoirs (EPA/NES data).

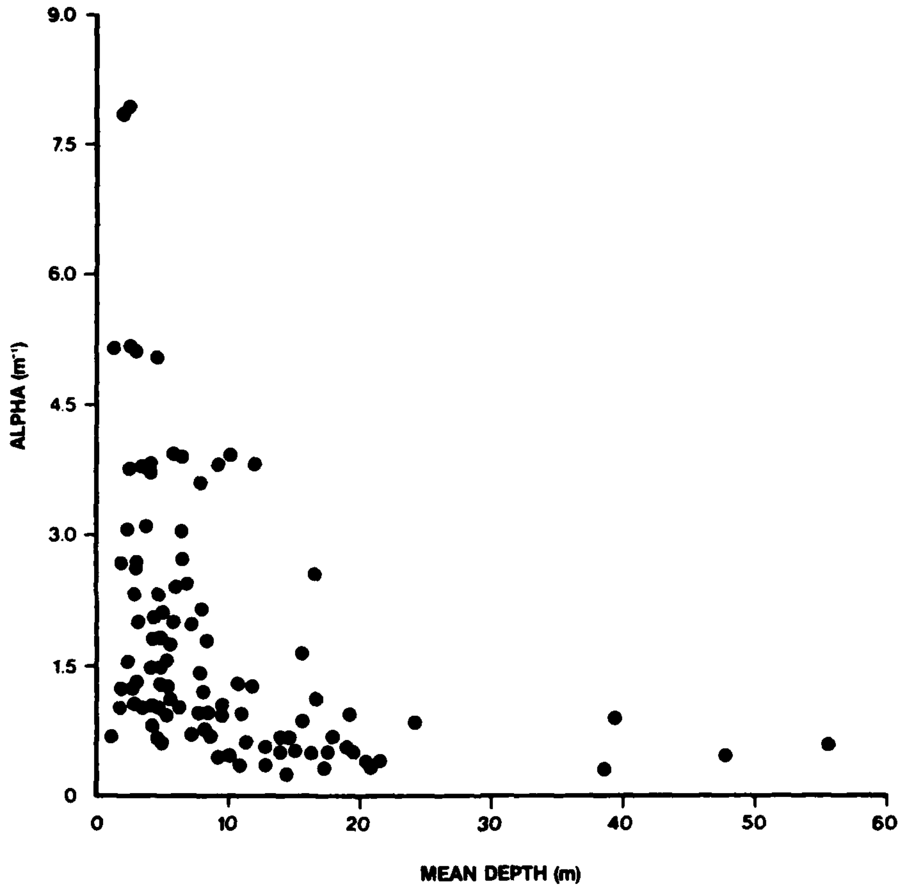


Figure 25. Non-algal turbidity vs. mean depth in USAE reservoirs (EPA/NES data).

319. The inverse relation between alpha and mean depth has implications for lake management by artificial circulation. A large mixed depth and high alpha value are both advantageous for control of algal blooms by light limitation. But an inverse correlation between mean depth and alpha makes it unlikely that both variables are high within the same lake. On the other hand, nonalgal turbidity as measured by alpha may increase after artificial mixing due to resuspension of sediments. The trade-offs between large mixed depth, high alpha, and clear water must be carefully evaluated before application of destratification techniques to algal bloom control.

320. Morphometic characteristics of artificially mixed reservoirs are included in Table 18 for comparison with USAE reservoirs. Overall, the reservoirs in which artificial mixing experiments have been conducted are smaller than USAE reservoirs in the EPA/NES compendium. For each morphometric parameter the range of the mixed reservoirs overlaps the mean of the USAE reservoirs. Also some large USAE reservoirs (e.g., Allatoona, Eufaula) are represented in both data sets. The influence of reservoir size on the effectiveness of various aeration/circulation techniques has not been well investigated. Nevertheless, it is evident that the impact of artificial destratification and hypolimnetic aeration devices on reservoirs as large as Allatoona (48 km^2) and Eufaula (415 km^2) will be localized (e.g., see "ARTIFICIAL CIRCULATION, Partial Mixing").

Reservoir fisheries

321. A comprehensive review of reservoir fisheries will not be attempted here. Instead, the purpose of this section is to refer the reader to a sampling of fisheries literature that is particularly germane to application and evaluation of aeration/circulation techniques in reservoirs.

322. In a description of fishery compartments and population rate coefficients for reservoir ecosystem models, Leidy and Jenkins (1977) present an overview of USAE reservoir fisheries from a regional perspective. After examining variation of species composition, total standing crop, and feeding guilds within and among major drainage areas, they concluded that most reservoirs within the same drainage system had similar fish species and total standing crops. However, significant year-to-year variation in response to environmental parameters was common to all reservoirs, and within a drainage area

Evaluation of Alternative Techniques

326. The selection of a reservoir aeration technique must be based on a detailed evaluation of various treatment options with respect to site-specific water quality problems and management goals. The following section considers previous evaluations of aeration techniques and describes a general evaluative procedure for selecting the best solution to a low DO problem.

Previous studies

327. Several studies have provided general evaluations of aeration/circulation techniques. For example, King (1970b) compared overall oxygenation efficiencies, practical advantages and disadvantages, and annual costs of various aeration techniques, including diffused-air mixing, oxygen injection, turbine aeration, cascade aeration, and mechanical-pump mixing. Since the ranges of efficiencies are similar for various methods of aeration, technique selection must be based on other factors such as practical applications and relative costs. Turbine aeration and reservoir circulation appeared inexpensive compared to other aeration techniques.

328. After a survey of water utilities AWWA (1971) evaluated artificial destratification of reservoirs on the basis of operator-perceived improvements in water quality, adverse impacts, and cost of equipment purchase, installation, and operation. Although their results indicated widespread problems associated with mixing, the benefits were sufficient to justify costs. In a brief discussion of oxygenation efficiencies and equipment selection, Leach (1974) proposed two critical factors for development of optimum designs based on efficiency and cost-effectiveness. The first was assessment of radial limits and oxygenation gradients arising from specific systems. The second factor was additional research knowledge of the variable biotic responses to destratification and hypolimnion aeration. Finally, Pastorok et al. (1980) evaluated artificial circulation and hypolimnetic aeration with respect to technical design, operational problems, and alternative responses of lake biota.

329. Speece (1975) examined a wide variety of aeration techniques for treatment of low discharge DO at Clark Hill Reservoir. Criteria for evaluation included high oxygenation efficiency, ease of installation and operation, minimal impact on temperature and dissolved nitrogen levels downstream, minimal loss of power-generating

one or more reservoirs might deviate greatly from the norm. Other evaluations of fish standing crop, harvest, and predator-prey systems in relation to morphoedaphic factors and climatic variables are given by Jenkins (1968), Hall (1971), Aggus and Lewis (1978), Leidy and Jenkins (1977), Clepper (1979), and Grieb et al. (in press).

323. Talmage and Coutant (1980) reviewed recent studies of thermal tolerance in fishes and other aquatic organisms. With specific reference to predator-prey interactions, Coutant et al. (1979) examine the influence of temperature alterations on fish behavior. Radiotelemetry has been particularly useful in unraveling the complexities of habitat selection behavior and thermal preferences of fishes (e.g., Schaich and Coutant 1980).

324. Leidy and Jenkins (1977) provide a summary of temperature optima and lethal tolerance limits for common fish species in USAE reservoirs. As expected, salmonid species exhibit the lowest thermal optima for growth, with preferred temperatures for different species ranging from 12 - 16^{o} C. Gizzard shad probably prefer temperatures in the vicinity of 16 - 18^{o} C. These species might be susceptible to thermal disturbance due to lake warming by artificial circulation. Warmwater fishes, such as centrarchids, cyprinids, ictalurids, and percids (Leidy and Jenkins 1977), might benefit from higher temperatures throughout a lake after mixing.

325. Doudoroff and Shumway (1967) provided dissolved oxygen criteria for the protection of fish. Davis (1975) reviewed the minimal dissolved oxygen requirements of aquatic life, including freshwater fishes. In general, DO concentrations of at least 5 mg/l are desirable for the maintenance of good game fish populations (EPA 1976). Fish can survive for short periods under anoxic conditions, but long-term exposure to DO concentrations less than 2 mg/l will produce considerable mortality in desirable game populations. In a review of the influence of dissolved oxygen on freshwater fish, Shumway and Palensky (1975) concluded that "growth rates, embryonic development, and swimming performance of both warmwater and coldwater fishes can be impaired by the availability of oxygen even when concentrations are reduced only slightly below air-saturation levels."

capacity, low initial costs, and low operating costs. Speece (1975) recommended upstream injection of gaseous oxygen into the hypolimnion as an efficient and cost-effective solution to low DO problems at Clark Hill (also, see discussion of actual experiments above). In addition, he concluded that continuous oxygen injection does not cause adverse environmental impacts or disturb thermal stratification. By comparison, all other aeration methods had serious drawbacks (Table 20). It should be emphasized that any one of the techniques in Table 20 might be a preferred solution to another water quality problem at some other site.

330. Nicholas and Ruane (1975) provided an extensive evaluation of various aeration techniques relative to a goal of discharge aeration at Fort Patrick Henry Dam. Their conclusions about the effectiveness of each method are summarized in Table 21. Essentially, their initial problem and the results of their evaluation are the same as those of Speece (1975). Upstream oxygen injection was recommended over all other aeration methods for elevation of discharge DO. Neither Nicholas and Ruane (1975) nor Speece (1975) considered alternative responses of lake biota to aeration/circulation techniques.

331. Fast et al. (1976) reviewed designs for hypolimnetic aerators and estimated oxygenation efficiency and costs for three systems at San Vicente Reservoir, California. While the partial air-lift design had the greatest capital cost, pure oxygen injection by side-stream pumping had the greatest operating cost. The full air-lift system required the least investment initially and during operation; also it was almost twice as efficient as the other systems in terms of oxygen dissolved per kilowatt-hour.

Evaluation procedure

332. Initial evaluation of aeration techniques relative to site-specific needs involves clear definition of water quality problems and management goals as well as information on past performance of treatment options at other sites. Once a technique is put into operation, continuing evalution requires reformulation of goals and monitoring of treatment effectiveness. Figure 26 outlines a general approach to the evaluation of aeration/circulation techniques.

333. Definition of problems and goals. Once the water quality problem(s) has (have) been identified, the first step in the

TABLE 20. DISADVANTAGES OF VARIOUS TECHNIQUES FOR DISCHARGE AERATION AT CLARK HILL RESERVOIR[a]

Technique	High Capital Cost	Impractical	Low Efficiency	Power Loss	Raise Discharge Temperature	Raise Discharge N_2 Gas
Surface Aeration	X	X	X		X	X
Diffused Air	X	X	X		X	X
Spillway	X	X		X	X	X
Selective Withdrawal	X	X		X		
Penstock Air Injection			X			X
Multilevel Intake	X	X			X	
Submerged Weir		X	X		X	
Local Destratification	X		X		X	X
Penstock O_2 Injection			X			
Sidestream Oxygenation		X	X			
Pulsed O_2 Injection	X	X	X			

[a] Summary of evaluation by Speece (1975). All disadvantages are relative to the preferred technique: continuous hypolimnetic injection of gaseous oxygen.

TABLE 21. APPLICABILITY OF VARIOUS AERATION METHODS FOR FORT PATRICK HENRY DAM (FROM NICHOLAS AND RUANE 1975)

Conditions Under Which Applicable Aeration Technique is to be Applied	Group I Reservoir Aeration: Destratification 1. Mechanical Pumping 2. Diffused Air	Group I Reservoir Aeration: Hypolimnion Aeration 1. Diffused Air 2. Diffused Oxygen	Group II Selective Withdrawal: Submerged Weir 1. Inflexible 2. Flexible	Group II Selective Withdrawal: Multi-Level Intakes	Group III Aeration of Reservoir Releases: Turbine Venting	Group III: U-Tube Aeration 1. Compressed Air 2. Oxygen Gas	Group III: Mechanical Aerators	Group III: Weir Aeration	Group III: Side-Stream Supersaturation	Group III: Oxygen Injection Upstream 1. Penstock 2. Diffuser 3. Downflow Bubble Contact	Group III: Tailwater Diffusers 1. Oxygen 2. Compressed Air
Coldwater tailwater	- -	+ +	- -	-	?	+ +	+	+	+	+ + +	+ ?
Tailrace deeper than 10'					+				+		+ +
High DO increase	- -	? ?	+ +	+	-	+ +	?	+	+	+ + +	+ ?
Fluctuating reservoir pool			- +								
Minimal effect on power production	+ +	+ +	+ +	+	?	- -	-	-	-	? + +	+ -
Minimal increase in dissolved nitrogen	? ?	- +	+ +	+	?	- +	+	?	+	+ + +	+ ?
Low Capital Cost	+ +	- -	- -	-	+	- -	-	-	-	+ + +	+ -

Note: + indicates a relatively positive effect of the particular aeration method.
- indicates a relatively adverse effect of the particular aeration method.
? indicates an unknown effect on the condition indicated.

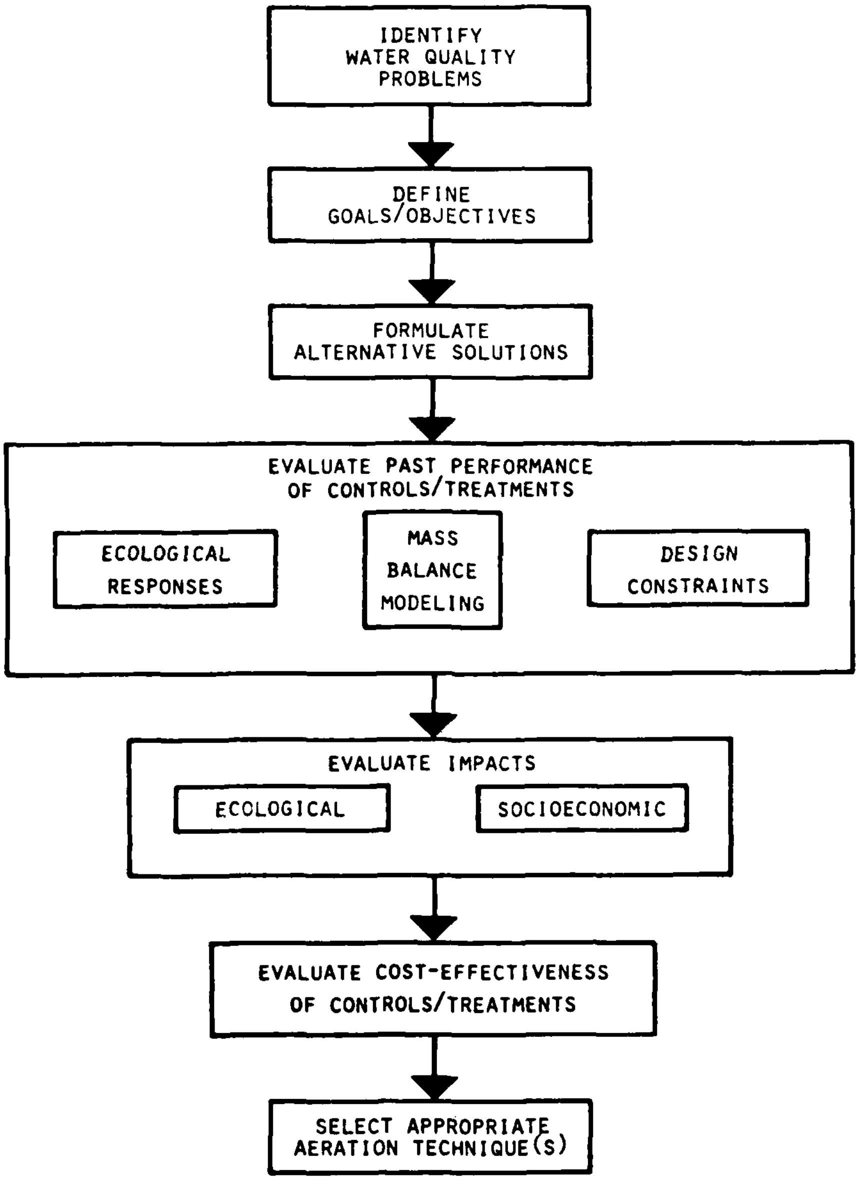


Figure 26. General procedure for evaluation of aeration techniques.

evaluation procedure is to define management goals. This step may consist of a simple statement of dissolved oxygen criteria/standards. In most cases, however, it is desirable to formulate specific goals and objectives for various components of the reservoir system. Some examples of objectives for aeration projects include: (a) control algal blooms; (b) reduce iron/manganese concentrations; (c) minimize internal nutrient loading; (d) increase water transparency; (e) reduce evaporation losses; (f) enhance fisheries yield; and (g) improve downstream fish habitat. The selection of management goals and objectives is critical to evaluation of past performance since the effectiveness of any technique can be judged only in relation to the specified objectives. Opposite evaluations may arise from different goals/objectives. For example, artificial destratification may be effective at reducing iron/manganese concentrations throughout the reservoir, but increases in temperature of reservoir releases following mixing treatment may be intolerable due to adverse effects on downstream fish habitat. Likewise, cost/benefit evaluations vary with goal choice. In many cases, objectives may have to be reformulated after an initial evaluation of techniques, especially when two or more objectives are in conflict or cost-effective solution(s) cannot be found.

334. Evaluation of past performance. The evaluation of past performance consists of three phases: mass balance modeling, assessment of ecological responses, and examination of design constraints. Mass balance modeling is used to characterize responses of the primary variable, dissolved oxygen. This step may consist of a simple accounting of oxygen supply and demand for the entire lake. More complex models involve simulation of oxygen exchange rates at the lake surface (Smith et al. 1975), oxygen transfer from air bubbles (Neilson 1974), and oxygen uptake rates in sediment and water (Cornett and Rigler 1979; Charlton 1980). Input/output calculations form the basis for the determination of oxygenation efficiency, a measure often used to compare the effectiveness of various aeration techniques (e.g., Leach 1974; Smith et al. 1975; Speece 1975; Fast et al. 1976). Tolland (1977) offers a critique of oxygenation efficiency and destratification efficiency as measures of treatment effectiveness.

335. Ecological responses are examined to determine the benefits of certain techniques with respect to target variables, e.g.,

phytoplankton abundance, water transparency, fish harvest, or system parameters, e.g., species diversity, stability. The potential for alternative responses related to species composition and community structure should be evaluated for each technique. Multivariate water quality indicators, such as the Lake Evaluation Index (Porcella et al. 1979), may be especially useful in characterization of ecological responses.

336. Finally, the evaluation of past performance examines the following design criteria: (a) feasibility, (b) practicality, (c) efficiency, (d) reliability, and (e) cost-effectiveness.

337. As discussed above, previous studies have used a number of these criteria (e.g., Speece 1975; Nicholas and Ruane 1975; Fast et al. 1976). The details of an engineering analysis vary with specific physical characteristics of the treatment. With a restoration device like a hypolimnetic aerator, the evaluation might use mathematical models to examine diffuser design, oxygen input capacity, and energy efficiency (e.g., Lorenzen and Fast 1977).

338. Evaluation of adverse impacts. Once the past performance of a technique has been reviewed, it is necessary to evaluate the site-specific ecological and socioeconomic impacts. Although this assessment may be a predictive exercise, it is based on a consideration of known impact from past experience at other sites. The evaluation might also consider possible mitigative actions required to alleviate adverse impacts.

339. Evaluation of cost-effectiveness. Cost-effectiveness of any given technique should be assessed within the context of an overall reservoir management plan. When a complex series of objectives is proposed, combinations of techniques may prove more cost-effective than any aeration method in isolation. Numerous economic models are available for determination of cost/benefit ratios; some simple approaches have already been considered (e.g., see above Speece 1975; Fast et al. 1976).

PART VI: RECOMMENDED RESEARCH

340. Various authors have offered research recommendations in the past (e.g., King 1970b; Toetz et al. 1972; Pastorok et al. 1980). Many of these recommendations have been followed in recent work, although the plea for a long-term research effort has generally been ignored. The list of recommendations below is based in part on future research suggested by Pastorok et al. (1980):

a. The importance of timing in destratification experiments suggests a need for research into thermal/chemical disturbance patterns and seasonal succession of phytoplankton. Interrelations among zooplanktivorous fish predation, grazing intensity on the phytoplankton, and phytoplankton community composition should be examined in light of selection for grazer-resistant forms (e.g., Ceratium) and the potential for nuisance algal blooms.

b. The relationships among reservoir morphometry, trophic state, and structure and composition of biological communities need to be investigated further relative to alternative outcomes of artificial circulation and hypolimnetic aeration experiments. Integration of mathematical models predicting peak algal biomass with conceptual models explaining shifts in phytoplankton species composition could provide a basis for testable hypotheses about mechanisms behind alternative lake responses. Changes in alpha, nutrient levels, and algal productivity with mixed depth variation should be evaluated in whole lake experiments to determine the relative importance of nutrients and light for limitation of peak biomass/productivity levels at different mixing intensities.

c. There is a need for simulation models and mathematical analysis of trophic responses to artificial mixing. For example, little information is currently available for predicting quantitative responses of fish and zooplankton to variation of mixed depth. New models for higher trophic levels could be linked with existing models for phytoplankton productivity and biomass.

d. The role of artificial circulation and hypolimnetic aeration in control of internal nutrient loading requires clarification. The relative importance of external nutrient loading vs. nutrient regeneration from sediments needs to be defined for various reservoir types.

e. For all aeration techniques, there is a need to standardize the measure of oxygenation efficiency, so that results of different studies can be compared

easily in an objective manner. Other performance-related measures that require attention are cost-effectiveness functions and destratification efficiency.

f. Observational/experimental designs should include at least two years of pretreatment data, replicated manipulations, and replicated controls. Within-lake controls such as large enclosures or unaffected stations are desirable. Results obtained from enclosure experiments should be further evaluated with respect to the capacity of microcosms to mimic whole lake systems.

g. For selected aeration techniques, spatial gradients in response parameters should be mapped under various operating conditions. Horizontal distribution of effects and localized mixing experiments need special attention.

h. The long-term responses of reservoir systems to various aeration treatments require further investigation. Fish populations may take several years to reach new equilibria after habitat manipulation. Other areas of special interest include changes in benthic macroinvertebrates, sediment composition, and internal nutrient loading during extended periods of treatment.

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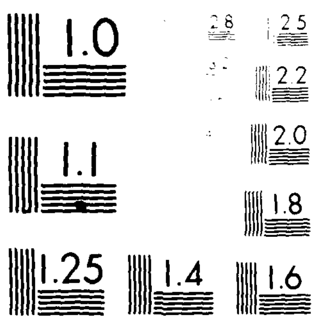
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Zison, S.W., W.B. Mills, D. Deimer, and C.W. Chen. 1978. Rates, constants, and kinetics formulations in surface water quality modeling EPA-600/3-78-105. U.S. Environ. Prot. Agency, Athens, Georgia. 335 pp.

APPENDIX A: ANNOTATED BIBLIOGRAPHY OF AERATION/ CIRCULATION EXPERIENCES

This bibliography covers the period from January, 1972, through December, 1980. It is intended to serve as an update to the literature search conducted by Toetz et al. (1972). The primary literature search was performed by computer using the DIALOG system. Additional references were obtained from extensive personal contacts, Dissertation Abstracts, and review of recent journals.

The general format of the present bibliography is similar to the DIALOG library system format:

AUTHOR

CITATION

ABSTRACT

DESCRIPTORS

IDENTIFIERS

SOURCE

Many of the citations, abstracts, and keywords (descriptors and identifiers) were obtained from DIALOG using appropriate data bases including: NTIS, BIOSIS, SCISEARCH, COMPENDIX, AQUATIC SCIENCES, and [illegible]ES ABSTRACTS. In some cases, the original author abstract (or summary) and keywords were used. Information was taken verbatim from the source, except for minor editorial changes. The origin of abstracts and keywords is indicated under the heading SOURCE. When information from the outside sources was incomplete, the abstract and keywords were written by Tetra Tech personnel.

Albertson, O.E., and D. Digregorio. 1975.
BIOLOGICALLY MEDIATED INCONSISTENCIES IN AERATION EQUIPMENT PERFORMANCE.
J. Water Pollut. Control Fed. 47:976-988.

Various tests were performed to verify and evaluate an oxygen transfer phenomena related to the biological activity level. Until now, all steady state aeration equipment evaluations have been predicted based on gas transfer theory, which predicts oxygen transfer is independent of oxygen uptake rate. The oxygen transfer evaluations performed at several activated sludge plants revealed a relationship between mixed liquor oxygen uptake rate and the measured standard oxygen transfer capacity. The conclusion reached was that direct transfer of oxygen from gas bubbles present within the mixed liquor to the microorganisms is responsible for the phenomena. Biological systems could be designed to reflect the relative respiration rates that characterize the specific operation.

DESCRIPTORS: Aeration, Oxygenation, Uptake Rates, Transfer Rates
IDENTIFIERS: Aerator Efficiency, Aeration Theory
SOURCE: Tetra Tech

Anonymous. 1972.
CORRECTING OXYGEN-POOR WATER.
Compressed Air 77:12-13.

The project described involved the aerating of Table Rock Lake, in the vicinity of the hydroelectric power dam, by means of ten large, construction-type portable compressors, designed to run quietly. The result of the first operational test of the aeration system, using two 1200-cfm Ingersoll-Rand Whisperized Spiro-Flo compressors, was the raising of the dissolved oxygen content below the dam from 4 to 6 ppm.

DESCRIPTORS: Water Treatment, Aeration, Compressors
IDENTIFIERS: Water Aeration System, Artificial Aeration
SOURCE: Dialog

Banks, R.B., and F.F. Herrera. 1977.
WIND AND RAIN AND SURFACE REAERATION.
J. Environ. Eng. Div., Amer. Soc. Civil Eng. 103:489-504.

Over the years, considerable research has been conducted on the subject of surface reaeration coefficients in estuaries. In contrast, not much is yet known about the magnitude of this coefficient in lakes and lagoons. Some studies indicate that wind action is important in establishing the rate of oxygen transfer across the surface of a lake or lagoon. In addition, it appears that the effect of rainfall may be important in reaeration in some lakes. In the present study, analyses were made of the effects of wind and rain on reaeration. Expressions were developed relating the rate and power of a rainfall to the surface reaeration coefficient. It was also determined that the direct addition of oxygen from oxygen-saturated raindrops can be an important factor in reaeration.

DESCRIPTORS: Aeration, Surface Water, Winds, Rainfall

IDENTIFIERS: Estuaries
SOURCE: Dialog

Barnes, M.D. 1977.
AN EVALUATION OF ARTIFICIAL CIRCULATION AS A MANAGEMENT TECHNIQUE FOR INCREASING BIOLOGICAL PRODUCTION AND FISH GROWTH IN A SMALL OHIO LAKE.
Ph.D. Dissertation, Ohio State University, Columbus, Ohio. 268 pp.

A 2.6-ha eutrophic impoundment in southern Ohio, which contained a population of stunted bluegills, was artificially destratified and circulated with compressed air during the summers of 1974 and 1975 to evaluate the technique as a means of increasing forage abundance and accessibility, habitat, and growth rates of fishes. Water chemistry, phytoplankton as chlorophyll and phaeophytin, zooplankton, and benthic macroinvertebrates were studied before and during artificial circulation, and reasons for changes in these parameters are given. Fish habitat was greatly expanded by aeration of the profundal waters, and chironomid larvae and oligochaetes invaded the profundal sediments, from which they had previously been absent. Feeding habits and growth rates of bluegills did not change signifigantly during artificial circulation. Reasons for the failure of artificial circulation 'o increase bluegill growth rates are discussed, and recommendations for the use of artificial destratification and circulation in the management of warmwater fisheries are presented.

DESCRIPTORS: Destratification, Diffused Air, Eutrophic, Bluegills, Water Quality, Phytoplankton, Fisheries Management
IDENTIFIERS: Aeration, Destratification
SOURCE: Author, Tetra Tech Keywords

Barnes, M.D., and B.L. Griswold. 1975.
EFFECTS OF ARTIFICIAL NUTRIENT CIRCULATION ON LAKE PRODUCTIVITY AND FISH GROWTH.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975.

The effects of artificial circulation and destratification of a small eutrophic lake were studied over 3 summers. Oxygen demand in the circulating lake seemed too high to allow rapid decomposition of organic detritus and release of limiting nutrients until late in the experiment. Plankton crops declined and fish stocks were depleted by about 67%. Oxygenation and warming of the hypolimnion encouraged extension of benthic forage, and this in conjunction with decreased population pressure seemed to enhance growth of the remaining fish. Prolonged circulation may be necessary in some lakes to achieve desired nutrient increases, but the technique shows great promise in extension and enhancement of fish habitat and forage and in the elimination of undesirable segments of a population.

DESCRIPTORS: Circulation, Destratification, Eutrophication, Oxygenation, Mixing
IDENTIFIERS: Artificial Circulation, Diffused Air
SOURCE: Author, Tetra Tech Keywords

Barnett, R.H. 1975.
CASE STUDY OF REAERATION OF CASITAS RESERVOIR.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975.

The 8-year reaeration program at Casitas reservoir has demonstrated that water quality in a large fresh water reservoir can be successfully and economically managed by means of diffused air injection.

Water quality problems in Casitas reservoir which were caused by manganese and hydrogen sulfide accumulations in the hypolimnion during summer months have been eliminated by reaeration.

Water quality problems in waters served from the Casitas reservoir distribution system which were caused by objectionable taste and odors, high pH and high water temperatures prior to reaeration have been successfully controlled as a result of increasing the depth of usable water from only 20 ft (6.1 m) to 100 ft (30.5 m) or more during summer periods.

Air injection diffusers in Casitas reservoir should be suspended well above the reservoir bottom to avoid bringing manganese in suspension from the bottom sediments during periods of reaeration.

A major fishery for rainbow trout has been established in Casitas reservoir as a direct result of reaeration.

DESCRIPTORS: Reservoir, Aeration, Water Quality, Hypolimnion, Fish
IDENTIFIERS: Rainbow Trout, Destratification, Diffused Air
SOURCE: Author, Tetra Tech Keywords

Bengtsson, L., and C. Gelin. 1975.
ARTIFICIAL AERATION AND SUCTION DREDGING METHODS FOR CONTROLLING WATER QUALITY.
Proc. Symp. on Effects of Storage on Water Quality, Water Res. Centre, Medmenham, England.

The lakes reported in this paper did not recover even several years after the diversion of sewage, probably because of polluted sediments. Depending on the lake morphology, one of three restorative techniques was used to improve the water quality. In a relatively shallow lake destratification by aeration was used; in a deep stratified lake hypolimnetic aeration was used; and in a shallow lake suction dredging was used.

As a result of the aeration experiments, an effective hypolimnetic aerator "LIMNO" has been developed by Atlas Copco and is commercially available. This new aerator can operate at any depth and stays operable throughout the winter. Hence with these techniques, the quality of runoff now replaces polluted sediments as the key to manipulating a lake ecosystem.

DESCRIPTORS: Suction Dredging, Water Quality, Aeration, Sediments, Pollution Wastewater, Lake, Destratification
IDENTIFIERS: Hypolimnetic Aeration, Destratification, Lake Restoration

SOURCE: Tetra Tech

Bernhardt, H. 1974.
TEN YEARS EXPERIENCE OF RESERVOIR AERATION.
pp. 483-495. In: S.H. Jenkins (ed). Seventh Internat. Conf. on Water Pollut. Res., Paris.

Long-term experience with hypolimnic aeration using the first apparatus developed by the author for the Wahnbach reservoir has shown that it is possible to prevent anaerobic conditions at the bed of the reservoir during summer stagnation. The apparatus used must be powerful enough to cover the oxygen requirements in the microlayer which depend on the extent of bioproductivity. Artificial aeration is best controlled by means of daily measurements of oxygen, manganese, iron, phosphorus, and organically bound carbon in the microlayer.

DESCRIPTORS: *Oscillatoria rubescens*, *Asterionella formosa*, *Melosira italica*, Eutrophication, Aeration, Water Quality
IDENTIFIERS: Hypolimnetic Aeration, Reservoir
SOURCE: Dialog, Tetra Tech Identifiers

Bernhardt, H. 1978.
DIE HYPOLIMNISCHE BELUFTUNG DER WAHNBACHTALSPERRE [HYPOLIMNIC VENTILATION OF THE WAHNBACH RESERVOIR]
Gas Wasserfach Wasser Abwasser 119:177-182.

The author demonstrates that it is possible, with limited financial means and relatively low operating costs, to ventilate a reservoir with a capacity of 40,000,000 m^3 and a length of about 5 km with only one ventilator installed at the point of greatest depth, so that the temperature during the summer months remains constant and the sediment-water layer can be maintained in an aerobic state during the entire summer period. In German.

DESCRIPTORS: Reservoirs, Cleaning, Water Treatment, Aeration
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Dialog, Tetra Tech Identifiers

Bernhardt, H., and A. Wilhelms. 1975.
HYPOLIMNETIC AERATION AS A MEANS OF CONTROLLING REDOX PROCESSES ON THE BOTTOM OF A EUTROPHIC RESERVOIR.
Verh. Internat. Verein. Limnol. 19:1957-1959. Abstract only.

Overloading of phosphate and nitrogen compounds during its 20-yr lifetime has caused progressive eutrophication of Wahnbach Reservoir. A hypolimnetic aeration system has been used successfully to prevent anaerobic conditions on the reservoir bottom during summer stagnation and autumnal partial circulation. Aeration over a 30- to 40-m distance within a tube enriches the oxygen content of the water to about 10 mg/l O_2. Waste gases are vented and water is returned to the hypolimnion at a depth of 15 m via another vertical tube.

Large amounts of dead biomass reach the lake bottom; and through mineralization processes, Mn^{++} and $PO_4^{\equiv}$ are released to the microlayer (0-5 cm) of water above the sediment if insufficient oxygen is present. When less than 4 mg/l O_2 is present in the microlayer, orthophosphate ions are released at the rate of 0.03 mg P m^{-2} day^{-1}. Release of orthophosphate is related to loss of $PO_4^{\equiv}$ from cell substances as well as reduction of ferric iron compounds. Fe^{+++} is not released during the initial stages leading to anoxic conditions, however. Mn^{++} concentrations in the microlayer are a reliable indicator of the intensity of reduction processes taking place at the sediment-water interface.
DESCRIPTORS: Eutrophication, Hypolimnion, Aeration, Reservoir, Sediment-Water Interactions
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Tetra Tech

Bianucci, G., and E.R. Bianucci. 1979.
OXYGENATION OF A POLLUTED LAKE IN NORTHERN ITALY.
Effluent Water Treat. J. 19:117-128.

Lake Ghirla, a highly polluted lake in northern Italy, was subjected in 1976 to a reclamation programme employing the pure-oxygen aeration method of Righetti. This article reports on the feasibility study, the methodology employed, and chemical analyses following the treatment programme which indicate that the favourable physico-chemical and biological effects of oxygenation have persisted. The lake has since been re-opened for bathing and aquatic sports, while sewage treatment measures are being investigated.
DESCRIPTORS: Freshwater Pollution, Waste Water Treatment, Oxygenation
IDENTIFIERS: Aeration, Sewage Treatment, Water Reclamation, Pollution Clean-Up
SOURCE: Dialog

Bjork, S. 1973.
RESTORING LAKES IN SWEDEN.
Tech. Rev. 76:1-10.

This article presents four lake restoration projects, three in Sweden and one in Tunisia. The shallow lake Trummen (Sweden) and Lake Tunis (Tunisia) and the deep Jarla Lake all receive large amounts of sewage and industrial wastewater. In shallow Hornborga Lake (Sweden), the water level had been drastically lowered, and aquatic macrophytes were a nuisance.

Beneficial results were obtained using sediment pumping in Lake Trummen, hypolimnetic aeration in Jarla Lake, and vegetation removal in Hornborga Lake. Hypolimnetic aeration increased dissolved oxygen in lower waters while reducing phosphorus, ammonia, iron, and manganese levels.
DESCRIPTORS: Waste, Sewage, Aeration, Sediment, Pumping, Lake, Wastewater

IDENTIFIERS: Hypolimnetic Aeration, Sediment Pumping, Vegetation Removal
SOURCE: Tetra Tech

Bowles, L.G. 1972.
A DESCRIPTION OF THE SPATIAL AND TEMPORAL VARIATIONS IN SPECIES COMPOSITION AND DISTRIBUTION OF PELAGIC NET ZOOPLANKTON IN THE CENTRAL POOL OF EUFAULA RESERVOIR, OKLAHOMA, WITH COMMENT ON FORCED AERATION DESTRATIFICATION EXPERIMENTATION.
Trans. Kansas Acad. Sci. 75: 156-173.

Zooplankton samples were taken in the central pool of Eufaula Reservoir, Oklahoma, to determine if forced aeration destratification affected spatial and temporal patterns of distribution and species composition. Antecedent conditions were determined by taking temperature and oxygen data January-July, 1968. Zooplankton samples were taken April-July, 1968. All three types of data were taken during aeration in August and afterward, in September, 1968. Eufaula Reservoir was found to be a temperate monomictic lake with stratification occurring in late June or early July and circulation in September. A total of 27 species of Cladocera, Copepods, and Rotifera were found. Diaphanasoma leuchtenbergianum, Diaptomus clavipes, and Polyarthra sp. were the most abundant of each group respectively, but at times, 2 or 3 species shared numerical dominance within the groups. Forced aeration had no apparent effect on the zooplankton community. This result may have been due to aerated water being drawn through the dam and sampling stations located upstream from the pumping station.
DESCRIPTORS: Diaphanosoma leuchtenbergianum, Diaptomus clavipes, Polyarthra sp., Cladocera, Copepods, Rotifera, Temperature, Oxygen
IDENTIFIERS: Forced Aeration, Destratification
SOURCE: Dialog, Author Abstract, Tetra Tech Identifiers

Bowles, B.A., I.J. Powling, and F.L. Burns. 1979.
EFFECTS ON WATER QUALITY OF ARTIFICIAL AERATION AND DESTRATIFICATION OF TARAGO RESERVOIR.
Department of National Development, Australian Water Resources Council. Technical Paper No. 46. Australian Government Publishing Service, Canberra. 239 pp.

The physical, chemical and biological characteristics of Tarago Reservoir were investigated under natural conditions and during artificial destratification by aeration between December 1974 and June 1977. Dissolved oxygen, iron, manganese and plant nutrient concentrations, together with temperature, zooplankton and phytoplankton populations were measured for all or most of the study period. Catchment investigations and measurements of primary production and light penetration were restricted to summer periods.

A destratification unit of the aerator type was developed, and installed at the Outlet Tower of Tarago Reservoir. The unit cost $2000 to build and install, and an annual operating cost of $600-$1200 was estimated to maintain the reservoir in destratified

condition. Operating costs were dependent on whether destratification was used before the onset of stratification, or after it had taken place - the former being the cheaper operation.

The destratification equipment was capable of maintaining isothermal, oxygenated conditions to the depth of the aerator level, and iron and manganese concentrations were successfully controlled. Light penetration increased during destratification, due to the photodestruction of colour, but there were not increases in phytoplankton populations. The greater penetration was more than offset by the increased mixed depth and thus the plankton remained light limited.

DESCRIPTORS: Aeration, Circulation, Water Quality, Phytoplankton, Zooplankton, Primary Production, Reservoir

IDENTIFIERS: Diffused Air, Destratification

SOURCE: Author, Tetra Tech Keywords

Brown, R.J. 1980.
AERATION OF SEWAGE LAGOONS, RESERVOIRS, AND STREAMS.
National Technical Information Service, Springfield, Virginia. 237 pp.

The worldwide reports cited in this bibliography cover both sewage aeration lagoons as well as the mechanical aeration of streams and reservoirs. The section on aeration lagoons covers their design and performance in treating both municipal, industrial, and agricultural wastes. The second section covers reports on the use of mechanical aerators to improve the water quality of lakes, rivers, and reservoirs. (This updated bibliography contains 230 abstracts, 13 of which are new entries to the previous edition.)

DESCRIPTORS: Lagoons (Ponds), Aeration, Stream Pollution, Reservoirs, Bibliographies, Aerators, Sewage Treatment, Water Pollution Control, Design, Industrial Wastes, Sewage, Agricultural Wastes, Lakes, Rivers

IDENTIFIERS: Aerated Lagoons, Oxidation Lagoons, Destratification

SOURCE: Dialog

Brynildson, O.M., and S.L. Serns. 1977.
EFFECTS OF DESTRATIFICATION AND AERATION OF A LAKE ON THE DISTRIBUTION OF PLANKTONIC CRUSTACEA, YELLOW PERCH, AND TROUT.
Wisc. Dept. Natur. Resour. Tech. Bull. No. 99. 22 pp.

To improve living conditions and expand the living zone for fish and their prey, dissolved-oxygen-poor Mirror Lake (5.3 ha, maximum depth 13 m) in central Wisconsin was artificially aerated during 1972-74.

After destratification (total aeration) of Mirror Lake in September 1973, trout and yellow perch and their primary prey, the *Daphnia*, occupied the entire lake. Before destratification of Mirror Lake, they were limited mainly to the upper half of the lake because of low dissolved oxygen levels in the lower half.

Although *Daphnia* occupied the entire lake in September 1973, they did not show an increase in average number per liter. *D. pulicaria* doubled in average number per liter but *D. galeata*

decreased by two-thirds, leaving the total number of daphnids essentially static. In September 1974, however, Daphnia showed an increase of four-fold in average number per liter after total aeration. Unlike 1973, however, D. pulicaria decreased by one-half and D. galeata and D. retrocurva were the daphnids that increased, the latter over 10-fold.

The density of calanoid and cyclopoid copepods increased during both 1973 and 1974 after total aeration, but there was no significant change in the density of the relatively small cladocerans, Bosmina longirostris and Diaphanosoma leuchtenbergianum, after aeration.

Only a small number of calanoid and cyclopoid copepods were found in the stomachs of yellow perch, while none were found in the stomachs of brook, brown, and rainbow trout from Mirror Lake even though there were as many large copepods (1 mm and larger) as there were large daphnids. Stomachs of age 1 domesticated brown and rainbow trout stocked in Mirror and Larson Lake, respectively, did not contain daphnids or copepods one week to one month after they were stocked in these lakes. Their diets were comprised mainly of terrestrial insects that were dominated in early autumn by winged ants.

DESCRIPTORS: Mixing, Aeration, Plankton, Crustacea, Yellow Perch, Trout, Lake
IDENTIFIERS: Destratification, Diffused Air
SOURCE: Author, Tetra Tech Keywords

Burns, F.L. 1977.
LOCALIZED DESTRATIFICATION OF LARGE RESERVOIRS TO CONTROL DISCHARGE TEMPERATURES.
Prog. Water Technol. 9:53-63.

Temperature stratification occurs in many Victorian reservoirs in summer, resulting in water temperatures of up to 24 degrees C in the upper layers, and down to 9 degrees C in the lower layers. For reservoirs having outlets only in this cold water region, the temperatures of summer releases to the river may therefore be well below normal summer river temperatures. This may have ecological effects on the river unless provision is made for breaking up the stratification or installing higher outlets. This paper describes an investigation involving hydraulic model studies, using salt solutions to reproduce stratification, supported by full-scale field tests, to develop a destratification installation for the 180 m deep, 4,000,000 Ml capacity Dartmouth Dam at present under construction on the Mitta Mitta river in Victoria. A model scale relationship was developed for artificial aeration, and, using this together with the Froude model relationship for water jets, an effective system was developed for producing local destratification in the vicinity of the outlets at Dartmouth. The model results indicate that a combined system of aeration and high-energy water jets will produce substantial increases in the temperature of water releases from the 60 m deep outlet. They also indicated that large outflows from the outlet will assist in this destratification action.

DESCRIPTORS: Reservoirs (Water), Stratification, Thermal Structure, Hydraulic Models
IDENTIFIERS: Artificial Aeration, Temperature Effects, Water Temperature, Aeration, Reservoirs, Freshwater Ecosystems
SOURCE: Dialog

Caire, R., M. Amoroso, J. Crate, and R.E. Speece. 1978.
FINAL REPORT 1978 CLARK HILL LAKE OXYGENATION STUDY.
Prepared for U.S. Army Corps of Engineers, Savannah District.

This study explored the field performance of the oxygenation equipment in Clark Hill Lake during 1978. Various baffle types and positions relative to the oxygen injection site were tested to obtain the maximum amount of the oxygenated water in the withdrawal zone of the dam. Properly designed baffles placed more than 80 percent of the oxygenated water in the withdrawal zone, yet the baffles do not appear to be cost-effective. Ribbon diffusers are superior to the square diffuser array used in the 1977 tests. Using an unbaffled ribbon diffuser in 1978, an oxygen maximum was positioned optimally within the withdrawal zone at a loading rate of 375 lb ft^{-2} day^{-1}.
DESCRIPTORS: Oxygen Injection, Dissolved Oxygen, Water Quality, Diffuser Design
IDENTIFIERS: Oxygenation, Reservoir Discharges
SOURCE: Tetra Tech

Carr, J.E., and D.F. Martin. 1978.
AERATION EFFICIENCY AS A MEANS OF COMPARING DEVICES FOR LAKE RESTORATION.
J. Environ. Sci. Health Part A. A13:73-85.

Various devices for aerating lakes as part of a lake restoration program have been proposed, but methods for comparing aeration efficiency of these devices have limitations. For example, the oxygen transfer coefficient, K_{La}, might be used, but the values depend upon the size of the lake and other factors that are not always adequately specified in the literature. It is shown that comparisons based on aeration efficiency, P, weight or oxygen transferred per horsepower-hour are superior to K_{La} values for rating efficiency of aerating devices. Aerator ratings based on values of P, however, must be sub-classified for four conditions (steady-state, non-steady-state, polluted, non-polluted). The derivation, advantages, and utility of aeration efficiency are described.
DESCRIPTORS: Lakes, (Water Pollution Control)
IDENTIFIERS: Aeration
SOURCE: Dialog

Cassidy, J.J. 1973.
REAERATION OF WATER WITH TURBINE DRAFT TUBE ASPIRATORS.
Completion Report 1 Jul 71-30 Jun 72. Missouri Water Resources Research Center, Columbia, Missouri. 23 pp.

The rate at which reaeration of water can be accomplished through introduction of air in turbine draft tubes was studied. A laboratory model simulating flow in a draft tube downstream from a turbine was constructed. Independent control of rate of flow of air and rate of flow of water was accomplished. Dissolved oxygen content of flow before and after reaeration was measured. Dimensionless parameters of aeration efficiency, Froude number and air to water content were plotted.
DESCRIPTORS: Reservoirs, Aeration, Dissolved Gases, Oxygen, Hydraulic Turbines, Dams, Hydraulic Models, Penstocks, Turbulence, Efficiency, Eductors, Head Losses
IDENTIFIERS: OWRR
SOURCE: Dialog

Chen, R.L., D.R. Keeney, and L.J. Sikora. 1979.
EFFECTS OF HYPOLIMNETIC AERATION ON NITROGEN TRANSFORMATIONS IN SIMULATED LAKE SEDIMENT WATER SYSTEMS.
J. Envir. Qual. 8:429-433.

Mechanical aeration of the anoxic hypolimnion of small, eutrophic, thermally stratified lakes and impoundments has been proposed as a temporary water quality improvement technique. We hypothesized that proper manipulation of this technique could lead to significant N loss through nitrification-denitrification. This hypothesis was examined by using simulated sediment-water and batch incubation systems, and the use of ^{15}N.

Aeration of an NH_4-enriched hypolimnion should lead to disappearance of ammonium and formation of nitrate. If the sediment had a high oxygen demand, nitrate should rapidly disappear once aeration was discontinued. Nitrate should also disappear, although more slowly, during aeration due to reactions at the sediment-water interface and in the surficial sediment. The amount of N removed from the sediments by nitrification-denitrification would vary widely, depending on the lake, but would not be as large as predicted from nonlabeled N mass balances due to assimilatory nitrate reduction (immobilization).

The results of this work indicate that nitrification is rapid, even at 10^{o} C, when the hypolimnion is aerated, and that denitrification and nitrate immobilization is equally rapid when aeration is stopped and the hypolimnion again becomes anaerobic. However, at least in Cox Hollow Lake sediments, a considerable amount of nitrate (up to about 60%) is immobilized rather than denitrified. Thus, the net loss of N from the lake system is much less than would be predicted from strictly inorganic N mass balance calculations, and hypolimnion aeration does not offer much promise as a method for removing N from lakes.
DESCRIPTORS: Wisconsin, USA; Thermal, Nitrification
IDENTIFIERS: Aeration, nitrogen, Redox Potential
SOURCE: Dialog, Author Abstract, Tetra Tech Identifiers

Cooley, T.N., P.M. Dooris, and D.F. Martin. 1980.
AERATION AS A TOOL TO IMPROVE WATER QUALITY AND REDUCE THE GROWTH OF HYDRILLA.
Water Res. 14:485-489.

Aeration of artificial, model lake systems was studied as a tool to improve water quality and to control the growth of a nuisance aquatic weed, *Hydrilla verticillata* (L.F.) Royle, which has been recognized as a plant pest since the mid-1960s. Aeration decreased the growth of *Hydrilla* by 20% fresh weight and 18% dry weight on average after 21 days. The effect was due to the oxygenation of the water and not the mechanical effect of the bubbles, as verified by studies using pure nitrogen. Aeration also affected water quality. Inorganic carbon decreased; nitrate-nitrite-nitrogen decreased, more slowly in test systems than in control systems; dissolved oxygen increased to saturation within 24 h and pH increased 0.5-1.5 unit over the period of study. Phosphate-phosphorus concentration was unaffected. The concentrations of zinc, calcium and iron decreased as well. The effect of aeration upon *Hydrilla* growth appears to be correlated with a decrease of iron. After 7 days, iron concentrations decreased to less than 20 ppb. Iron toxicity is proposed as the mechanism responsible for creating a limiting condition for *Hydrilla* growth.

DESCRIPTORS: Aeration, Aquatic Weed, Oxygenation, Weed Control, Lake Aeration, Nutrients

IDENTIFIERS: Improved Water Quality, Aquatic Weed Nuisance, Aeration Nutrient Effects

SOURCE: Author, Tetra Tech Keywords

Crate, J., R. Caire, R. Trice, and R.E. Speece. 1978.
FINAL REPORT 1977 CLARK HILL LAKE OXYGENATION STUDY.
Prepared for U.S. Army Corp of Engineers, Savannah District.

The reason for this study was to develop an aeration system which would use the cold water discharge of an impoundment to provide adequate water quality for maintenance of a downstream trout fishery. This report describes the results of the 1977 field studies in which 100 tons/day oxygen was injected continuously for 30 days at a point one mile upstream of the dam. Baffles placed directly in the bubble plume were effective in moving the oxygenated water to the withdrawal zone of the turbines. Greater incremental additions of dissolved oxygen were obtained by changing diffuser plates from 10 to 2 ft/min permeability and reducing loading from 4 to 1 ACFM. Maximum sustained DO in the turbine discharge averaged about 4.6 mg/l and DO enhancement was observed one mile upstream from the oxygen injection system.

DESCRIPTORS: Oxygen Injection, Water Quality, Diffusers, Dissolved Oxygen

IDENTIFIERS: Oxygenation, Reservoir Discharges

SOURCE: Tetra Tech

Damann, K.E. 1975.
EFFECT OF AERATION ON PERIPHYTON.
J. Phycol. 11 (Suppl):21-22.

A small dystrophic lake in upper New York State with a maximum depth of 8 m and marked thermal stratification has been the subject of regular year around limnological investigations. Emphasis has been placed upon the effect of continuous aeration on the chemical and physical parameters as they relate to periphyton production. Four fiber glass cylinders have been permanently located with two in water of approximately 4 m and two in the deepest water of 8 m. Two cylinders are continuously aerated with compressed air and two companion cylinders are maintained as control chambers. The water level is always above the top of the cylinders thus allowing for interchange of water and organisms between the open lake water and the experimental chambers. No ice cover ever develops over the aerated cylinders,while over 6 decimeters of ice is commonly found in all parts of the non-aerated portions of the lake. Homogeneity of chemical and physical parameters within the aerated cylinders was found to be very pronounced when compared to water direcly outside of the cylinders. Biological productivity expressed as periphyton biomass was found relatively abundant at all levels in the aerated cylinders from the surface to the the bottom of the lake. In non-aerated cylinders and in open water stations without cylinders, the periphyton was found decreasingly abundant to depths approaching 3 m and little or no growth was found from 4-7 m.

DESCRIPTORS: New York, USA, Lake, Thermal Stratification, Productivity
IDENTIFIERS: Aeration, Periphyton
SOURCE: Dialog, Author Abstract, Tetra Tech Identifiers

Darden, R.B., J. Imberger, and H.B. Fischer. 1975.
JET DISCHARGE INTO A STRATIFIED RESERVOIR.
Hydraulics Div., Amer. Soc. Civil Eng. 101:1211-1220.

An experimental investigation of the flow induced by a line jet in a linear-density stratified reservoir fluid is reported. Both buoyant and nonbuoyant jets were discharged into the stratified model and jet discharge and model length were varied. Experimental data indicate the two-dimensional flow field can be divided into three regions: (1) Open region above equilibrium level; (2) closed region below equilibrium level; and (3) a central jet with adjacent entrainment rotors. True steady-state flow was not achieved. The pattern of induced flow showed no distinctive changes when model length of jet discharge were varied, but the induced flow pattern showed appreciable changes when jet buoyancy was varied from neutral to buoyant. Maximum flow speed, rotor size, and entrainment were significantly increased for the buoyant jet.

DESCRIPTORS: Reservoirs, Flow, Water Jets, Entrainment, Theory
IDENTIFIERS: Jet Discharge
SOURCE: Author, Tetra Tech Keywords

Davis, J.M. 1980.
DESTRATIFICATION OF RESERVOIRS - A DESIGN APPROACH FOR PERFORATED-PIPE COMPRESSED-AIR SYSTEMS.
Water Services 84:497-504.

Water quality problems in reservoirs can be avoided by proper design of a mixing system to prevent thermal stratification. A design procedure is described in detail, including: (1) assumption of a design temperature profile, (2) calculation of total theoretical energy required to achieve destratification by overcoming stability and added heat input, (3) calculation of the quantity of free air delivery required at the compressor, (4) calculation of length and internal diameter of perforated pipe, (5) calculation of anchor weight required.

Where possible, the compressor should be electrically powered and have an air filter and cooling system for discharge air. Polythene pipe, including non-return and stop valves to prevent back-siphoning, should be positioned along a line perpendicular to the dam wall in deep water. Efficient operation of the mixing system depends on monitoring of water temperature and dissolved oxygen.

Approximate costs for compressors range from about 53.8 British pounds to 72 pounds per unit of air delivery (liter/sec) over the range of sizes considered (25-305 liter/sec). Approximate costs for polythene pipe are given also. Total cost of a mixing system will include installation expenses which vary with site conditions. As an example, total cost of a 100 liter/sec compressor delivering air a 7 bar with 500 m polythene pipe in a reservoir under construction will cost about 20,000 pounds.

DESCRIPTORS: Mixing, Diffused Air, Compressors, System Design, Reservoirs, Stability, Energy Input, Costs
IDENTIFIERS: Destratification, Aeration, Design
SOURCE: Tetra Tech

Davis, J.M., and R.W. Collingwood. 1978.
DESTRATIFICATION IN RESERVOIRS.
Water Services 82:487-488.

The nature of thermal stratification is illustrated and the problems resulting from deoxygenation are dealt with to prevent them from happening, rather than attempting to cure them once they have occurred. Two principal methods achieving this are outlined.

DESCRIPTORS: Reservoirs, Thermal Stratification, Water Resources, Research
IDENTIFIERS: Destratification
SOURCE: Dialog

Devick, W.S. 1972.
LIMNOLOGICAL EFFECTS OF ARTIFICIAL AERATION IN THE WAHIAWA RESERVOIR.
Job Completion Rep., Proj. F-9-2, Job 2, Study IV. Honolulu, Hawaii.

In an attempt to avert a major fish kill resulting from circumstances induced by an extended drought, an emergency floating

aeration system was installed in the Wahiawa Reservoir. Circulation had to be restricted to the upper waters due to the high oxygen demand in the hypolimnion and because the available equipment was not suitable for long-term operation. The system proved effective. The potential for a fish kill was reduced by increasing the depth of the fish survival zone, by increasing the total dissolved oxygen load, and by increasing the resistance to induced circulation with the oxygen-demanding deeper water by nocturnal cooling effects. A small but extended fish kill that occurred before the system was operational was probably limited by the initial aeration procedure. No fish kills caused by anoxia occurred after the system was fully operational, even though worse weather and lower water levels prevailed.
DESCRIPTORS: Fish Kill, Aeration, Hypolimnion, Reservoir, Mixing
IDENTIFIERS: Artificial Aeration
SOURCE: Author, Tetra Tech Keywords

Dortch, M.S. 1975.
HYDRAULIC DESTRATIFICATION.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975. 15 pp.

Parameters pertinent to hydraulic destratification of lakes have been investigated at the Waterways Experiment Station through the use of a laboratory model. Various pumping rates, diffuser sizes, and pumping arrangements (diffuser-intake orientation) have been tested under stratified conditions and compared for effectiveness. The results are part of a continuing effort to develop design guidance for prototype hydraulic destratification projects.
DESCRIPTORS: Hydraulics, Lakes, Stratification, Mixing
IDENTIFIERS: Hydraulic Destratification, Stratified Lakes
SOURCE: Author, Tetra Tech Keywords

Dortch, M.S. 1976.
CENTER SLUICE INVESTIGATION, LIBBY DAM, KOOTENAI RIVER, MONTANA. HYDRAULIC MODEL INVESTIGATION.
Final Report No. WES-TR-H-76-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. 62 pp.

The model study of the center sluice, Libby Dam, was conducted to determine the causes of and to develop means for preventing the cavitation damage experienced in the sluices. The study was conducted in a 1:200-scale model of the center sluice which reproduced the 'as-built' geometry of the bell-mouthed intake, emergency gate slot, regulating gate and gate well, and parabolic trajectory of the sluiceway. The model helped to define undesirable hydraulic conditions that have caused cavitation damage in the prototype structure. Through the use of the model, an aeration device was developed to ventilate the jet and prevent cavitation damage. The recommended aerator (type 7) provided a high degree of aeration without adversely altering flow conditions in the sluice.

A certain roof modification was suggested to prevent unstable flow and cavitation damage in the sluice intake.
DESCRIPTORS: Dams, Conduits, Hydraulic Models, Waterways, Rivers, Water Flow, Cavitation, Aeration, Pressure, Water Jets, Discharge, Flood Control, Reservoirs, Montana
IDENTIFIERS: Libby Dam, Sluice Gates, Lake Koocanusa, Aerators
SOURCE: Dialog

Dortch, M.S. 1979.
ARTIFICIAL DESTRATIFICATION OF RESERVOIRS; HYDRAULIC LABORATORY INVESTIGATION.
Tech. Rep. WES-TR-E-79-1, U.S. Army Engineer Waterways Experiment Station, Environmental and Water Quality Operational Studies. 45 pp. + App.

Methods of generating mixing in a density-stratified reservoir were experimentally investigated in a laboratory tank. Pneumatic (air bubbling) and hydraulic (water pumping) methods of destratification were studied, but efforts were concentrated on hydraulic destratification. The orientation of the diffuser and intake was found to influence the effectiveness of hydraulic destratification. Experimental results were used to relate mixing time to pumping conditions and reservoir size and stratification. The results are presented with the intent of being used for the planning and preliminary design of hydraulic destratification systems.
DESCRIPTORS: Reservoirs, Hydraulic Models, Water Quality, Environmental Protection, Test Methods, Experimental Data, Stratification, Water Pollution.
IDENTIFIERS: Reservoir Stratification, Environmental and Water Quality Operational Studies.
SOURCE: Author, Dialog Keywords

Dortch, M.S., and S.C. Wilhelms. 1978.
ENHANCEMENT OF RELEASES FROM A STRATIFIED IMPOUNDMENT BY LOCALIZED MIXING, OKATIBBEE LAKE, MISSISSIPPI.
Final Report No. WES-MP-H-78-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. 18 pp.

Tests were conducted at Okatibbee Lake, Mississippi, to evaluate the effectiveness of localized mixing for enhancing the quality of low-level, low-flow releases from a stratified impoundment. A low-energy mechanical pump (Garton pump) that consisted of a submerged ventilating fan driven by a 1.12-kw electric motor was positioned immediately upstream of and above the low-level intake. Epilimnion water was forced toward the lake bottom where it was mixed with hypolimnion water and then released through the fixed low-level flood control outlet. The quality of this water mixture was an improvement over the quality of the water released without the pump operating. It was estimated that the epilimnion water comprised about 50 percent of the total release. Use of a Garton pump to induce localized mixing upstream of a fixed low-level flood control outlet was demonstrated to be an effective and economical

means of improving the quality of low-flow releases from a stratified reservoir.
DESCRIPTORS: Limnology, Drainage, Reservoirs, Water Quality, Stratification, Mixing, Depth, Circulation, Temperature Gradients, Vertical Orientation
IDENTIFIERS: Okatibbee Lake, Water Pollution Control, Aeration, Pumps, Mississippi
SOURCE: Author, Dialog Keywords

Drury, D.D., D.B. Porcella, and R.A. Gearheart. 1975.
THE EFFECTS OF ARTIFICIAL DESTRATIFICATION ON THE WATER QUALITY AND MICROBIAL POPULATIONS OF HYRUM RESERVOIR.
Report No. PRJEW011-1, Utah Wat. Res. Lab. 182 pp.

Hyrum Reservoir, Utah, was studied for one year and then for a year following the initiation of artificial destratification. The redistribution of dissolved oxygen to the lower depths of the reservoir significantly increased the amount of habitat suitable for trout. The annual *Aphanizomenon* bloom increased during the first year after initiating destratification. The nitrogen cycle and the vertical distribution of bacteria were altered as a result of the elimination of the thermocline. During destratification the total suspended solids were correlated with the total coliforms. The water quality of Hyrum Reservoir was highly affected by annual runoff, spring and fall overturns, and destratification; sediments, the increased *Aphanizomenon* bloom, higher epilimnetic nutrient concentrations, more uniform microbial and nutrient distributions all resulted from these hydraulic factors working singly and in combination.
DESCRIPTORS: Aeration, Stratification, Hyrum Reservoir, Thermoclines, Dissolved Gases, Oxygen, Nutrients, Trout, Water Quality, Nitrogen Cycle, Runoff, Suspended Sediments, Coliform Bacteria, Hydraulics, Aquatic Microbiology, Seasonal Variations, Little Beaver River, Utah, Theses.
IDENTIFIERS: Dissolved Oxygen, Destratification, *Aphanizomenon*, Water Quality Data, Epilimnion, Eutrophication.
SOURCE: Dialog

Dudley, R.G., and R.D. Quintrell. 1979.
THE EFFECTS OF HYPOLIMNION OXYGENATION ON DOWNSTREAM BIOTA AT CLARK HILL DAM.
Final Rep., Contract No. DACW21-77-C-0087. U.S. Army Corps of Engineers. 68 pp. + App.

Oxygen injection into the hypolimnion of Clark Hill Reservoir during 1977 increased the dissolved oxygen content of waters below 10 m, although oxygen concentrations below 30-m depth were often less than 1 mg/l. Thermal stratification was slightly changed by oxygenation treatment, resulting in warm (21° C) hypolimnetic waters by late summer.

In downstream waters, treatment increased oxygen concentrations and prevented build-up of manganese and iron. Redox potential,

conductivity, alkalinity, and hardness did not differ significantly between control and treatment years. Changes in downstream fish populations due to hypolimnetic oxygenation were not apparent, although increased catches of fish at stations nearer the dam may have resulted from elevation of oxygen levels by treatment. Without hypolimnetic treatment, fishes in the Clark Hill tailwaters are normally tolerant of low dissolved oxygen. The downstream benthic fauna was depauperate, with low diversity due to dominance by Oligochaeta; treatment effects were not assessed due to lack of control data.
DESCRIPTORS: Reservoir, Oxygenation, Hypolimnion, Water Quality, Fish, Benthos
IDENTIFIERS: Hypolimnetic Oxygenation
SOURCE: Tetra Tech

Dunst, R.C., S.M. Born, P.D. Uttormark, S.A. Smith, S.A. Nichols, J.O. Peterson, D.R. Knauer, S.L. Serns, D.R. Winter, and T.L. Wirth. 1974.
SURVEY OF LAKE REHABILITATION TECHNIQUES AND EXPERIENCES.
Technical Report No. 75. Wisconsin Dept. of Natural Resources, Madison. 179 pp.

Excessive eutrophication of lakes is a serious international problem. There has been a great need for a comprehensive information source usable in developing future rehabilitation/protection programs. The state-of-the-art review represents an attempt to delineate the accomplishments of lake restoration-related activities worldwide. Information was acquired through an extensive mail survey (about 8,000 entries), cooperation of several international journals/newsletters, and a systematic literature search including foreign as well as domestic materials. The contents of the report consist of five major divisions: (1) identification, description and present utility of the various techniques; (2) compilation and description of individual past and/or ongoing restoration experiences (almost 600 accounts); (3) project methodology; (4) name and address of people providing pertinent information (over 300 respondents); and (5) literature references (more than 800 documents).
DESCRIPTORS: Lakes, Rehabilitation, Reviews, Conservation, Renovating, Project Planning, Water Reclamation, Identifying, Methodology, Aeration, Nutrients, Flushing, Documentation, Land Use, Dredging, Harvesting, Biological Productivity, Sewage Treatment
IDENTIFIERS: Eutrophication, Lake Restoration
SOURCE: Dialog

Fain, T.G. 1978.
EVALUATION OF SMALL-PORE DIFFUSER TECHNIQUE FOR REOXYGENATION OF TURBINE RELEASES AT FORT PATRICK HENRY DAM.
Report No. WM28-1-32-100. Tennessee Valley Authority, Division of Water Management, Water Systems Development Branch. 65 pp.

This report explored the various methods for reaerating water released through turbines. The oxygen injection method was chosen

because it allows high dissolved oxygen levels and does not destratify the lake.

Characteristics of a typical prototype oxygenation system were specified for Fort Patrick Henry Dam, based on design criteria of minimum of 6 mg/l DO in the discharge 99.8 percent of the time. Studies of various methods indicated that oxygen injection through diffusers immediately upstream from the turbine intakes appeared to be the best choice. The recommended system would demand $120,000 annual capital cost and $230,000 annual oxygen cost. The oxygen injection system tested at Fort Patrick Henry Dam could probably be used at other TVA dams after preliminary tests of flow patterns, oxygen absorption efficiency and other parameters at each site.
DESCRIPTORS: Turbine Aeration, Oxygen Injection, Dissolved Oxygen, Water Quality, Reservoir
IDENTIFIERS: Artificial Oxygenation, Reservoir Discharges
SOURCE: Tetra Tech

Fast, A.W. 1973a.
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON PRIMARY PRODUCTION AND ZOOBENTHOS OF EL CAPITAN RESERVOIR, CALIFORNIA.
Water Resour. Res. 9:607-623.

El Capitan Reservoir was continually and artificially mixed by using compressed air during the summers of 1965 and 1966. Mixing and reservoir volume increases resulted in more uniform physical and chemical conditions, aerobic conditions throughout the lake, increased primary production, increased depth distributions of zoobenthos, and zoobenthos population increases. Increased primary production was related to a decrease in algal depth distribution. This decrease was caused by incomplete destratification, since thermal microstratification persisted near the lake surface. Zoobenthos were distributed throughout the lake during mixing, whereas they were confined to shallow depths during well-stratified times. Water volumes increased three-fold during the study and greatly confounded interpretation of the mixing effects.
DESCRIPTORS: Zoobenthos, Mixing, Stratification
IDENTIFIERS: Artificial Mixing
SOURCE: Author, Tetra Tech Keywords

Fast, A.W. 1973b.
EFFECTS OF ARTIFICIAL HYPOLIMNION AERATION ON RAINBOW TROUT (<u>SALMO GAIRDNERI</u> RICHARDSON) DEPTH DISTRIBUTION.
Trans. Amer. Fish. Soc. 102:715-722.

Hemlock Lake, a eutrophic and meromictic Michigan lake, was artificially aerated by hypolimnetic aeration. This aeration system involved a special aeration tower and compressed air injection. Hypolimnetic oxygen concentrations increased from zero to saturation during aeration. Thermal stratification was gradually reduced by the aeration, but the lake remained thermally stratified for 10 weeks during aeration. Before aeration, rainbow trout (<u>Salmo gairdneri</u> Richardson) were limited to shallow depths by the

anaerobic hypolimnion. They distributed to the deepest depths soon after aeration began and occupied the entire lake during artifical aeration.
DESCRIPTORS: Hemlock Lake, Michigan, Compressed Air, Meromictic Thermal Stratification
IDENTIFIERS: Hypolimnetic Aeration, Aeration, Hypolimnion
SOURCE: Dialog, Tetra Tech Identifiers

Fast, A.W. 1973c.
SUMMERTIME ARTIFICIAL AERATION INCREASES WINTER OXYGEN LEVELS IN A MICHIGAN LAKE.
Prog. Fish-Cult. 35:82-84.

Hemlock Lake, a small eutrophic lake in Michigan, was artificially aerated to prevent winterkill oxygen concentrations within the lake. Increases in winter oxygen concentrations following summer artificial aeration were attributable to mixing, which increased the oxygen reserve at the time of the ice formation, and to the greatly reduced amount of decomposable organic matter apparently due to artificial aeration.

Artificial aeration during any one of three seasons (summer, autumn, or winter) may prevent winterkill. The most appropriate method and time of aeration will vary depending on limnological conditions.
DESCRIPTORS: USA, Fishes, Microorganisms, Oxidation, Organic Matter, Winter Kill Mortality
IDENTIFIERS: Aeration, Winterkill, Oxygenation
SOURCE: Dialog, Tetra Tech Abstract and Identifiers

Fast, A.W. 1975.
ARTIFICIAL AERATION AND OXYGENATION OF LAKES AS A RESTORATION TECHNIQUE.
Symposium on the Recovery of Damaged Ecosystems, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Artificial aeration is one of many lake restoration techniques. These techniques operate by modifying either the symptoms or causes of eutrophication. Those techniques which modify the cause of eutrophication operate by reducing either the inflow of nutrients to the lake (external loading), or the recycling of nutrients already in the lake (internal loading). Artificial aeration may reduce the internal loading rate by maintaining aerobic conditions throughout the lake, but the full consequences of this modification on internal loadings are still unknown. Artificial aeration can be accomplished either through the total mixing of the lake (destratification), or through aeration of the hypolimnion only without thermal destratification (hypolimnetic aeration). Each method of aeration has its unique attributes and beneficial impacts on the symptoms of eutrophication irrespective of their effects on nutrient loadings.
DESCRIPTORS: Oxygen, Aeration, Lake, Hypolimnion
IDENTIFIERS: Hypolimnetic Aeration, Artificial Aeration, Lake Restoration
SOURCE: Author, Tetra Tech Keywords

Fast, A.W.. 1979a.
ARTIFICIAL AERATION AS A LAKE RESTORATION TECHNIQUE.
pp. 121-131. In: Proc. Natl. Conf. Lake Restoration. U.S. Environ. Prot. Agency, Washington, D.C.

A large variety of lake aeration systems exist. They increase the oxygen content of the water through mechanical mixing or agitation, air injection, or the injection of pure oxygen. These systems either mix waters at all depths and cause thermal destratification, or they preserve the thermal gradient and aerate the bottom waters only. The effects of artificial aeration on nutrient concentrations and algal growth are poorly understood. In some cases they can either increase or decrease these parameters depending on a variety of circumstances. Destratification is probably beneficial for most warmwater fisheries, and hypolimnetic aeration can create or greatly expand the coldwater fishery potential of a lake. A new process for rearing coldwater fish in a lake has been invented. The rearing chambers float on the lake's surface, and the process may remove nutrients from the lake. Air injection into lakes can cause nitrogen gas supersaturation, and consequently fish kills downstream. Special care must be used when aerating a lake with bottom withdrawals.

DESCRIPTORS: Oxygen, Aeration, Lake, Hypolimnion
IDENTIFIERS: Hypolimnetic Aeration, Artificial Circulation, Destratification, Lake Restoration
SOURCE: Author, Tetra Tech Keywords

Fast, A.W., 1979b.
NITROGEN GAS SUPERSATURATION DURING ARTIFICIAL AERATION AT LAKE CASITAS, CALIFORNIA.
Prog. Fish-Cult. 41:153-154.

A study of Lake Casitas, California, showed that artificial aeration can cause nitrogen supersaturation relative to surface pressure. Nitrogen gas levels were measured by a tensiometer in the vicinity of the bubble plume in the lake and at distances up to 800 m from the bubble plume. After about 80 days of aeration at 46 m depth, N_2 levels in the zone of induced mixing were at 125 percent saturation relative to surface pressures. Below 46 m, N_2 concentrations were up to 140 percent saturation relative to the surface. No adverse effects on fishes were observed.

DESCRIPTORS: Artificial Aeration, Hypolimnion, Mixing, Surface Pressure Thermal Destratification, Gas Supersaturation, Nitrogen, Impoundment
IDENTIFIERS: Aeration, Hypolimnetic Aeration
SOURCE: Tetra Tech

Fast, A.W., and M.W. Lorenzen. 1976.
SYNOPTIC SURVEY OF HYPOLIMNETIC AERATION.
J. Environ. Eng. Div., Amer. Soc. Civil Eng. 102:1161-1173.

Hypolimnetic aeration/oxygenation is a means whereby thermal stratification can be maintained in a lake or reservoir and the hypolimnetic waters are oxygenated. Seventeen different hypolimnetic aerator/oxygenator designs are presented and analyzed, categorized as mechanical agitation systems, pure oxygen injection systems, and air injection systems. Air injection systems can be further subdivided into full air lift designs, partial air lift designs and downflow air injection. Of all the systems, the full air lift is probably the most efficient in terms of energy consumed to dissolve a given amount of oxygen. None are in widespread usage.
DESCRIPTORS: Water Treatment, Aeration, Reservoirs, Thermal Stratification, Lakes
IDENTIFIERS: Hypolimnion, Hypolimnetic Aeration
SOURCE: Dialog

Fast, A.W., and M.W. Lorenzen. 1978.
EFFECTS OF AERATION/MIXING ON LAKE BIOLOGY.
In: Mitchell, R. (ed). Water Pollution Microbiology. Vol. 2. Wiley Interscience, New York.

Techniques for aeration/circulation of eutrophic lakes were divided into two categories: destratification and hypolimnion aeration. Destratification methods include procedures which either mix a lake or provide aeration without maintaining a normal thermal structure. Hypolimnion aeration methods are designed to maintain the normal thermal structure of a lake while adding oxygen.

Both categories contain techniques which affect the physical, chemical and biological processes within a lake. Specifically, hypolimnetic aeration may significantly alter the zooplankton and benthic fauna in an environment. Artificial destratification can cause faster rates of organic matter decomposition as well as shifts in predominant organisms. Water quality parameters can be significantly improved using the mentioned procedures.
DESCRIPTORS: Aeration, Mixing, Destratification, Circulation, Oxygenation, Hypolimnion, Lake
IDENTIFIERS: Hypolimnion Aeration, Artificial Destratification, Artificial Aeration
SOURCE: Tetra Tech

Fast, A.W., and W.T. Momot. 1973.
THE EFFECTS OF ARTIFICIAL AERATION ON THE DEPTH DISTRIBUTION OF THE CRAYFISH ORCONECTES-VIRILIS IN TWO MICHIGAN LAKES.
Amer. Midl. Nat. 89:89-102

Crayfish (Orconectes virilis) usually exhibit seasonal depth distributions in certain northern Michigan lakes based on sex, age, and water temperature. After releasing attached young in shallow water, the adult females typically migrate to deeper cold water while the adult males remain in the warm shallow water. This pattern was thought to be related to the sexual maturation cycle. However, when two lakes were artifically aerated and destratified with compressed air, both sexes distributed throughout the lakes.

It is, therefore, postulated that under normal conditions of thermal stratification, the social aggression of the larger males forces the females into deeper, colder water and that this aggression is temperature-related. If oxygen or some other factor is not limiting, 10^{0} C seems to be the lowest temperature selected by O. virilis during the summer.
DESCRIPTORS: Temperature, Migration, Social Aggression
IDENTIFIERS: Artificial Aeration, Crayfish Migration
SOURCE: Dialog, Author Abstract, Tetra Tech Keywords

Fast, A.W., V.A. Dorr, and R.J. Rosen. 1975a.
A SUBMERGED HYPOLIMNION AERATOR.
Water Resour. Res. 11:287-293.
A new hypolimnetic aeration system is described. This system increased the hypolimnetic oxygen concentrations of Lake Waccabuc, New York, from 0.0 mg/l to over 4.0 mg/l, while at the same time preserving thermal stratification. These improvements and others created a suitable habitat for cold-water fish, but care must be exercised in the use of the system to avoid problems of nitrogen gas supersaturation.
DESCRIPTORS: Lakes, Improvement, Reservoirs, Thermal Stratification, Water Pollution, Analysis
IDENTIFIERS: Hypolimnetic Aeration Systems, Eutrophication
SOURCE: Dialog

Fast, A.W., M.W. Lorenzen, and J.H. Glenn. 1976.
COMPARATIVE STUDY WITH COSTS OF HYPOLIMNETIC AERATION.
J. Environ. Eng. Div., Amer. Soc. Civil Eng. 102:1175-1187.
Hypolimnetic aeration/oxygenation is a means of thermal stratification maintenance and oxygenation of hypolimnetic waters in a lake or reservoir. The process differs from destratification, where the objective is reduction or elimination of thermal stratification and oxygenation of the bottom waters. Hypolimnetic aeration/oxygenation greatly improves domestic and industrial water quality, satisfies downstream water release standards, creates suitable habitat for year long survival of coldwater fish, and otherwise benefits the environment. Methods of hypolimnetic aeration/oxygenation which use pure oxygen, a partial air lift pump and a full air lift pump are described and analyzed. Cost estimates for these systems at San Vicente Reservoir, California reveal that the full air lift design is substantially more efficient and less costly to operate.
DESCRIPTORS: Hypolimnion, Aeration, Oxygenation, Stratification
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Dialog, Tetra Tech Keywords

Fast, A.W., B. Moss, and R.G. Wetzel. 1973b
EFECTS OF ARTIFICIAL AERATION ON THE CHEMISTRY AND ALGAE OF TWO MICHIGAN LAKES.

Water Resour. Res. 9:624-647.

Two lakes were artificially aerated by using compressed air. Section Four Lake, an unproductive lake, was completely mixed, whereas Hemlock Lake, a eutrophic lake, had its hypolimion aerated but thermal stratification maintained. Chemical and algal changes in Section Four Lake during destratification were not great. Although phytoplanktonic production potentials increased during mixing, the phytoplankton standing crop appeared to decline slightly, possibly due to the increased mixing depth and turbidity. Hemlock Lake hypolimnetic anoxia and conditions associated with it were eliminated during aeration. The lake gradually destratified during aeration due to leaks in the aeration tower. These leaks also released nutrient rich water into the epilimnion, which promoted algal growth.

DESCRIPTORS: Mixing, Hypolimnion, Diffused Air, Eutrophic, Water Quality, Phytoplankton, Standing Crop, Species Composition, Primary Production

IDENTIFIERS: Destratification, Hypolimnetic Aeration, Phytoplankton

SOURCE: Author, Tetra Tech Keywords

Fast, A.W., W.J. Overholtz, and R.A. Tubb. 1975b.
HYPOLIMNETIC OXYGENATION USING LIQUID OXYGEN.
Water Resour. Res. 11:294-299.

A new system of hypolimnetic oxygenation called side stream pumping (SSP) is described. The SSP system uses liquid oxygen and a conventional water pump, whereas most other hypolimnetic oxygenation systems use compressed air and a special aeration chamber. The SSP system was tested in Ottoville Quarry, Ottoville, Ohio, during the summer of 1973. Hypolimnetic oxygen concentrations increased from less than 0.5 mg/l to over 8.0 mg/l during 2 months of operations, and thermal stratification was maintained. These improvements created a suitable habitat for cold-water fish, but care must be exercised in the use of the SSP system to avoid potential problems with high, free carbon dioxide concentrations.

DESCRIPTORS: Water Pollution, Analyses, Reservoirs, Thermal Stratification

IDENTIFIERS: Hypolimnetic Oxygenation Systems, Liquid Oxygen

SOURCE: Dialog

Ferraris, C.J., Jr., and J. Wilhm. 1977.
DISTRIBUTION OF BENTHIC MACROINVERTEBRATES IN AN ARTIFICIALLY DESTRATIFIED RESERVOIR.
Hydrobiologia 54:169-176.

A total of 76 taxa of benthic macroinvertebrates was collected from Ham's Lake, Oklahoma, during 1974 and 1975. The composition and density of the benthic assemblage was similar to that of other Oklahoma reservoirs. The number of species and density of macroinvertebrates decreased from March to the end of July, 1975. Species diversity and biomass did not change significantly with time. Number of species and species diversity decreased with depth

on all sampling periods. The most pronounced changes occurred between 4 and 5 m during periods of thermal stratification and hypolimnion anoxia. Artificial destratification removed the thermocline from Ham's Lake within 2 wk. More gradually the deep waters were reoxygenated. Destratification did not substantially alter the depth distribution of benthic macroinvertebrates until oxygen level of the deep water was increased.
DESCRIPTORS: Reservoir, Macroinvertebrates, Destratification
IDENTIFIERS: Benthic Macroinvertebrates, Species Diversity, Artificial Destratification
SOURCE: Author, Tetra Tech Keywords

Fike, R.A. 1979.
WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN.
South Dakota Cooperative Fishery Research Unit. Brookings. Office of Water Research and Technology, Washington, D.C. 73 p.

The use of molecular oxygen aeration under the ice cover as a method to prevent winterkill in Round Lake, South Dakota, was evaluated during the winter of 1977-1978. Physical, chemical and biological limnological conditions are documented for the period. Round Lake and other shallow eutrophic pothole lakes in South Dakota often suffer winterkill due to their high level of nutrients that promote rapid phytoplankton growth in summer. These phytoplankton die and decay rapidly consuming dissolved oxygen by catabolic processes in winter when the ice and snow cover prevents them from getting light. During the winter studied, the ice and snow cover was formed by December 20, and after that date phytoplankton numbers and chlorophyll concentration decreased.
DESCRIPTORS: Aeration, Limnology, Lakes, Oxygen, Winter, Physical Properties, Concentration (Composition), Ice, South Dakota, Evaluation, Biochemical Oxygen Demand, Dissolved Gases, Chlorophylls, Plankton
IDENTIFIERS: Winter Kill, Oxygen Injection
SOURCE: Dialog, Tetra Tech Identifiers

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979.
MIXING IN INLAND AND COASTAL WATERS.
Chapter 6, Mixing in Reservoirs. Academic Press, New York. 483 pp.

Chapter 6 begins with a brief description of the annual cycle of mixing and stratification in Wellington Reservoir, Australia. External energy sources for mixing include wind, stream inflow and outflow. Vertical mixing in the epilimnion is described with respect to penetrative convections and mixing due to weak winds versus severe winds. Even though the hypolimnion is generally very stable with large average Richardson numbers, there can be relatively vigorous vertical mixing in a local area at a particular time where energy density has been increased by some concentrating mechanism. Horizontal movements of epilimnetic waters range from little eddies to large gyres. Below the thermocline, stratification

usually dominates and mean motions consist of a set of interleaving density currents of great horizontal and small vertical extent. The discussion of outflow dynamics focuses on essential formulae for steady flow necessary to determine the quality of the outflowing water. Mixing of inflows involves entrainment of reservoir water by an inflowing stream and possible intrusion into horizontal strata at intermediate depths. The description of a numerical model of Wellington Reservoir shows how such work can be used to investigate management strategies based on inflow and withdrawal manipulations.
DESCRIPTORS: Reservoir, Circulation, Density, Inflow, Outflow, Convection, Wind, Stratification, Model
IDENTIFIERS: Basic, Reservoir, Natural Mixing
SOURCE: Tetra Tech

Forsberg, B.R., and J. Shapiro. 1980b.
PREDICTING THE ALGAL RESPONSE TO DESTRATIFICATION.
pp. 134-139. *In:* Restoration of Lakes and Inland Waters, EPA 440/5-81-010, U. S. Environmental Protection Agency, Washington, D. C.

The response of phytoplankton communities to artificial destratification has been quite variable. The mechanisms underlying this variability were investigated in eight field experiments in two Minnesota lakes. Polyethylene enclosures were used in controlled experimental designs to investigate specific response mechanisms. A mathematical model was developed to describe the community response under different mixing regimes. The peak concentration and total amount of chlorophyll a in the mixed layer were predicted to either increase, decrease or remain the same depending on changes in the mixed depth and the concentration of total phosphorus in the mixed layer following destratification. Changes in species composition during artificial circulation depended on the mixing rate achieved. Blue-green algae increased in relative abundance at the slower mixing rates while green algae and diatoms were favored at the fastest mixing rates. The shift to green algae only occurred during conditions of low pH and high nutrient availability associated with rapid mixing and is therefore most likely to occur when relatively deep productive lakes are rapidly mixed.
DESCRIPTORS: Mixing, Artificial Circulation, Experimental Enclosures, Phytoplankton, Blue-green Algae, Green Algae, Green Algae
IDENTIFIERS: Destratification, Diffused Air
SOURCE: Author, Tetra Tech Keywords

Garrell, M.H., A.M. Gibbs, and R.L. Miller. 1978.
MAINTENANCE OF A TROUT FISHERY BY AERATION IN A EUTROPHIC LAKE.
N.Y. Fish Game J. 25:79-82.

Before aeration treatment, Lake Waccabuc did not support a salmonid fishery because of high epilimnetic temperatures and anoxia in the hypolimnion during summer. A "LIMNO" hypolimnetic aerator maintained summer oxygen levels between 3.5 and 7.0 mg/l in the

hypolimnion. The metalimnion remained anoxic between 6 m and 8 m. Aeration maintained a suitable habitat for stocked rainbow trout, which fed mainly in the hypolimnion. Aeration fostered larger populations of white perch and yellow perch while preventing summer fishkills.
DESCRIPTORS: Habitat Improvement (Chemical), Eutrophic Lakes, Artificial Aeration, Aquaculture Techniques
IDENTIFIERS: Hypolimnion
SOURCE: Dialog, Tetra Tech Abstract

Garrell, M.H., J.C. Confer, D. Kirchner, and A.W. Fast. 1977.
EFFECTS OF HYPOLIMNETIC AERATION ON NITROGEN AND PHOSPHORUS IN A EUTROPHIC LAKE.
Water Resour. Res. 13:343-347.

The effects of hypolimnetic aeration on total P, NO_3-N, and NH_4-N in eutrophic Lake Waccabuc (New York) are described. This lake was aerated for two consecutive summers (1973 and 1974) by using the system previously described in a paper by Fast et al. (1975a). Although reductions in hypolimnetic P concentrations appeared in the first summer, they failed to reappear during the second summer. NH_4-N and NO_3-N concentrations are compared with those in an unaerated control lake, Lake Oscaleta (New York). Very slight changes in relative hypolimnetic NH_4-N concentrations and corresponding increases in hypolimnetic NO_3-N concentrations are seen. The overall results suggest that the aerated lake is subjected to substantial external loading, which may mask aeration effects on the internal nutrient cycles.
DESCRIPTORS: Hypolimnion, Diffused Air, Water Quality
IDENTIFIERS: Hypolimnetic Aeration, Phosphorus, Nitrogen
SOURCE: Author, Tetra Tech Keywords

Garton, J.E. 1978.
IMPROVED WATER QUALITY THROUGH LAKE DESTRATIFICATION.
Water Wastes Eng. 15:42-44.

Low energy water pump circulation can reverse the natural process of stratification that sometimes causes taste and odor problems in lake water supplies. In temperate climates lakes become stratified thermally and chemically in summer and the thermocline prevents mixing of the often anoxic hypolimnion with the oxygen-rich epilimnion. Thus overturn in autumn may cause the entire water column to go to near zero oxygen with high levels of ammonia. This condition is sometimes lethal to fish and induces complaints from people using the water. Tests are being carried out with large diameter, low velocity, downward pumping pumps which economically make the temperature of the water column nearly uniform so that nighttime cooling and the passage of weak cool fronts aided by wind-induced circulation, cause the surface waters to fall to the bottom of the lake carrying the oxygen with it. Another application being examined is the use of a pump which circulates water upwards to keep a lake clear of ice and so prevent the formation of an oxygen-deficient zone below the ice and aid in fisheries management.

DESCRIPTORS: Thermal Stratification, Anoxic Conditions, Water Circulation, Water Quality, Artificial Aeration, Lakes
IDENTIFIERS: Ice, Water Mixing
SOURCE: Dialog

Garton, J.E., J. Wilhm, R.E. Punnett, D. Barker, and E. Cover. 1979.
LOW ENERGY MECHANICAL DESTRATIFICATION AND REAERATION OF RESERVOIRS.
Oklahoma Water Resources Research Inst., Stillwater. Office of Water Research and Technology, Washington, D.C. Final Technical Completion Rept. 90 pp.

A cluster of 16 axial flow units was used to destratify a lake having a surface area of 951 hectares. Complete destratification was not achieved. However, a significant reduction of the anoxic hypolimnion was accomplished. The penetration of a low-velocity jet was limited by density differences and accurately predicted. Attempts were made to correlate seasonal changes in water near the bottom, the sediments, and the physiological changes in benthic invertebrates with the dissolved oxygen content and temperature of the lake water. Examination of the vertical variation of physiochemical conditions indicated that mechanical pumping did not improve water quality of the water 1 m above the bottom at either the 15 m stations in the arms or in the central pool.
DESCRIPTORS: Aeration, Reservoirs, Water Pollution Control, Lake Arbuckle, Propeller Pumps, Dissolved Gases, Oxygen, Performance Evaluation, Seasonal Variations, Invertebrates, Temperature Measurement, Phosphorus, Field Tests, Concentration (Composition), Iron, Manganese, Copper, Zinc, Sediments, Oklahoma
IDENTIFIERS: Reaeration, Destratification, Thermal Stratification, Bioindicators
SOURCE: Dialog

Garton, J.E., and H.R. Jarrell. 1976.
DEMONSTRATION OF WATER QUALITY ENHANCEMENT THROUGH THE USE OF THE GARTON PUMP.
Oklahoma Water Resources Research Inst., Stillwater, Oklahoma. Technical Completion Rept. 25 pp.

In temperate climates, many lakes stratify during the summer. A typical stratified lake will have a warm oxygen-rich epilimnion, a thermocline, and a colder oxygen depleted hypolimnion. High levels of iron, manganese, hydrogen sulfide, and ammonia and dissolved hydrocarbons may occur in the hypolimnion. Many efforts have been made to destratify lakes, primarily by air bubbling. These methods require large energy inputs. A low-energy destratifier using a 1.83 m propeller to pump water downward from the surface has been used successfully to destratify a 100 acre lake (35 feet deep) for three years. This project involved using the pump on Lake Okatibbee, a broad, shallow lake of approximately 1,537 ha (3,800 ac) with a maximum depth of slightly over ten meters. From the data obtained it is evident that the Garton Pump can indeed induce water from the epilimnion to flow downward into the intake structure so that the

water actually released has the characteristics of the near surface water of the lake.
DESCRIPTORS: Water Pollution Control, Stratification, Pumps, Lake Okatibbee, Thermoclines, Hydrocarbons, Pumping, Reservoirs, Iron, Hydrogen Sulfide, Ammonia, Manganese, Mississippi
IDENTIFIERS: Garton Pumps, Destratification, Hypolimnion, Epilimnion
SOURCE: Dialog

Garton, J.E., and C.E. Rice. 1976.
IMPROVING THE QUALITY OF WATER RELEASES FROM RESERVOIRS BY MEANS OF A LARGE DIAMETER PUMP.
Final Technical Report, September 1973-March 1976, prepared by Oklahoma Water Resources Research Institute, Stillwater, Oklahoma. 36 pp.

In temperate climates, many lakes stratify during the summer. A typical stratified lake will have a warm oxygen-rich epilimnion, a thermocline, and a colder oxygen-depleted hypolimnion. High levels of iron, manganese, hydrogen sulfide, and ammonia and dissolved hydrocarbons may occur in the hypolimnion. Many efforts have been made to destratify lakes, primarily by air bubbling. These methods require large energy inputs. A low-energy destratifier using 42-inch propellers to pump the water downward from the surface has been used successfully to destratify a 100-acre lake (35 feet deep) for 3 years. This project was an attempt to apply the same kind of device to Lake Arbuckle, a 2,400-acre, 90-foot-deep lake in south central Oklahoma. A 16.5-foot aircraft propeller was used to pump approximately 200,000 gallons per minute downward. Although the lake stability index was decreased by half, a corresponding reduction in the oxygen distribution index did not occur until the fall overturn. The oxygen content in the outlet waters near the pump was increased 1 to 2 mg/l during the critical summer months.
DESCRIPTORS: Water Pollution Control, Axial Flow Pumps, Stratification, Lake Arbuckle, Reservoirs, Pumping, Water Quality, Oxygen, Aeration, Iron, Hydrocarbons, Hydrogen Sulfide, Manganese, Ammonia, Oklahoma
IDENTIFIERS: Hypolimnion, Destratification
SOURCE: Dialog

Garton, J.E., and R. Punnett. 1978a.
DESTRATIFICATION OF LAKE ARBUCKLE, OKLAHOMA, 1977.
ASAE, St. Joseph, Michigan. Paper 78-2085. 12 pp.

A cluster of 16 axial flow units was used to destratify a lake having a surface area of 951 hectares. Complete destratification was not achieved. However, a significant reduction of the anoxic hypolimnion was accomplished. The penetration of a low velocity jet was limited by density differences and was accurately predicted.
DESCRIPTORS: Lakes, Temperature Distribution, Water Supply, Water Quality
IDENTIFIERS: Thermal Stratification, Eutrophication, Destratification

SOURCE: Dialog

Garton, J.E., and R.E. Punnett. 1978b.
WATER QUALITY IMPROVEMENT IN SMALL PONDS.
Res. Proj. Tech. Completion Rept. A-065-OKLA, Oklahoma Water Resour. Res. Inst. 14 pp.

A simple method of determining destratifier design criteria was developed for water quality improvement in small ponds using a Garton pump. The method is based upon two major objectives: (1) to penetrate to the bottom of the pond with downward pumped surface waters; and (2) to pump a volume of water equal to the normal hypolimnion every two days. The data are presented in tabular form. From the table the advantage of using larger diameter pumps is apparent.

DESCRIPTORS: Ponds, Water Pollution Control, Ham's Lake, Lake of the Arbuckles, Pumps, Flow Rate, Design, Temperature Gradients, Oxygen, Dissolved Gases, Pumping, Prototypes, Mathematical Prediction, Tables (Data), Oklahoma
IDENTIFIERS: Destratification, Hypolimnion
SOURCE: Dialog

Garton, J.E., C.E. Rice, J.M. Steichen, and J.E. Quintero. 1974.
LOW ENERGY MECHANICAL METHODS OF RESERVOIR DESTRATIFICATION.
Final Report July 1971-June 1974, Oklahoma Agricultural Experiment Station, Stillwater, Oklahoma. 54 pp.

The objective was to evaluate reservoir stratification causing degradation of large volumes of water each summer. Many attempts have been made to destratify lakes. Generally, destratification devices have large power requirements. The first phase of the research involved the design, construction and testing of a high volume, low head destratification pump. In the second phase this axial flow pump was modified and was capable of moving 0.99 cubic meters per second of water from near the surface to near the bottom of the lake using 373 watts. The chief objective of the second phase was to determine the effectiveness of the pump as a destratification device.

DESCRIPTORS: Water Pollution, Reservoirs, Axial Flow Pumps, Surface Waters, Stratification, Bottom Water, Pumping, Design, Physical Properties, Water Masses, Water Quality, Chemical Properties, Efficiency, Construction, Test Methods, Aeration
IDENTIFIERS: Destratification, Reaeration
SOURCE: Dialog

Garton, J.E., R.G. Strecker, and R.C. Summerfelt. 1978.
PERFORMANCE OF AN AXIAL FLOW PUMP FOR LAKE DESTRATIFICATION.
pp. 336-346. In: W.A. Rogers, ed. Proc. 13th Annu. Conf. S.E. Assoc. Fish Wildl. Agencies.

A propeller pump was operated for 120 days on a lake of 40 ha surface area in north-central Oklahoma in the summer of 1975 to

accomplish artificial destratification. The pump created a downflow of well-oxygenated surface water by means of a 1.82-m-diameter propeller located 1.8 m below the lake's surface. The pump produced a flow of 1.72 m^3/sec equivalent to 12.9% of total lake volume per day, at 17 rpm with a 1.0 h.p. electric motor. Four days of pumping eliminated thermal stratification, it raised the temperature of the hypolimnetic water 9.5° C, but increased surface temperature less than 1° C. Thereafter the entire water column remained isothermal (27-29° C) during the summer. Dissolved oxygen at 5 m increased from 0.2 to 4.3 mg/l after the first day of pumping. Thereafter DO levels at 5 and 9 m depths were above levels observed in 1973 and 1974. In mid-July 100% of the lake's volume contained more than 5 mg/l DO. BOD levels averaged 2.3 mg/l before pumping but 1.2 mg/l after pumping began. Turbidity did not change substantially with pumping but the variation at 1.5 and 9 m depths was reduced.
DESCRIPTORS: Thermal Stratification, Discontinuity Layers, Destratification, Aeration
IDENTIFIERS: Water Circulation, Methodology, Lakes, Water Mixing
SOURCE: Dialog

Garton, J.E., R.C. Summerfelt, D. Toetz, J. Wilhm, and H. Jarrell. 1977.
PHYSIOCHEMICAL AND BIOLOGICAL CONDITIONS IN TWO OKLAHOMA RESERVOIRS UNDERGOING ARTIFICIAL DESTRATIFICATION.
Oklahoma Water Resour. Res. Inst. Rept. No. REC-ERC-77-6.

The purpose of this study was to develop more efficient methods of reservoir reaeration and to determine the environmental effects of reservoir destratification. The Garton pump, a low energy, axial flow device, is designed to pump water from the surface downward to destratify and reaerate lakes and reservoirs. A 1.07-m-diameter version of the device was tested in Ham's Lake (40-ha surface area, 10-m maximum depth) near Stillwater, Okla., in 1973 and 1974, and Lake of the Arbuckles (951-ha surface area, 27-m maximum depth) near Sulphur, Okla., in 1974 and 1975. This report describes vertical variations in the two reservoirs of: (1) temperature, dissolved oxygen, and several other physiochemical parameters; (2) species composition and density of the algae populations; (3) species composition and diversity of zooplankton; (4) species composition, diversity, and density of benthic macroinvertebrates; and (5) vertical (bathymetric) distribution and growth of fish.
DESCRIPTORS: Aeration, Water Pollution Control, Limnology, Lake of the Arbuckles, Ham's Lake, Ecology, Design, Performance Evaluation, Pumps, Temperature, Mixing, Oxygen, Dissolved Gases, Fishes, Benthos, Zooplankton, Algae, Nutrients, Comparison, Oklahoma
IDENTIFIERS: Destratification, Species Diversity
SOURCE: Dialog

Gebhart, G.E., and M.D. Clady. 1977.
EFFECTS OF MECHANICAL MIXING IN RESERVOIRS ON SEASONAL AND ANNUAL GROWTH RATES OF FISHES.
Tech. Completion Rept. A-069-OKLA, Oklahoma Water Resour. Res. Inst. 50 pp.

The effect of mechanical mixing carried out on Lake Arbuckle, Oklahoma, in 1977, was investigated by measuring seasonal and annual growth rates of fish. In 1976 and in 1977 after mixing, fish were taken using gill nets, and scales and spines were examined to reveal the effect on growth rates. The mixing attempt to destratify the reservoir and improve fish environment did increase the habitat available to the fish. Seasonal growth rates of gizzard shad and channel catfish, which are bottom feeders, were greater during the destratified period when more of the bottom area was available for feeding. Pelagic feeders like white crappie and white bass were less adversely affected by the loss of bottom habitat. Mechanical mixing increased the amount of available fish habitat in late summer which probably benefited growth, but the best growth occurred when available fish habitat was expanded in early summer. To maximize growth, mixing should begin in early May with the objective of preventing vertical stratification.
DESCRIPTORS: Stratification, Aeration, Fresh Water Fishes, Lake Arbuckle, Water Pollution, Mixing, Conservation, Growth, Catfishes, Bass, Seasonal Variations, Summer, Oklahoma
IDENTIFIERS: Crappie, Habitats, Destratification, Water Pollution Effects (Animals)
SOURCE: Dialog

Gebhart, G.E., and R.C Summerfelt. 1976.
EFFECTS OF DESTRATIFICATION ON DEPTH DISTRIBUTION OF FISH.
J. Environ. Eng. Div., Amer. Soc. Civil Eng. 102:1215-1228

The authors' observations in Lake of the Arbuckles, Oklahoma, in 1973-1975 indicate that depth distributions of gizzard shad, white crappie, freshwater drum, and black bullhead were markedly affected by conditions of stratification. During stratification the distribution of all species except the bullhead was limited largely to oxygenated water above the hypolimnion. Fish depth distribution increased substantially after the fall overturn. Operation of an axial flow pump in the summers of 1974-1975 appeared to cause turnover 1 month earlier than shown by the authors for 1973, and data of other workers for 1969-1970.
DESCRIPTORS: Hypolimnion, Stratification, Fish, Destratification
IDENTIFIERS: Destratification
SOURCE: Dialog, Tetra Tech Keywords

Givler, C., R. Aubert, E. DiMond, and R.E. Speece. 1977.
OXYGENATION TESTS AT CLARK HILL LAKE.
Final Report. Prepared for U.S. Army Corps of Engineers, Savannah District. 106 pp.

This study evaluates diffusers and their location in front of the dam to find the most efficient position for the oxygenation system. Diffusers with a standard permeability rating of 2 feet/minute gave superior oxygen absorption when compared with diffusers having a permeability of 0.5 feet/minute and 10 feet/minute. Findings suggest that continuous oxygen injection from

closely spaced diffusers about one mile upstream of the dam provide maximum efficiency. For the 140-ft injection depth, the recommended loading rate of about 500-1000 lb/day oxygen per square foot of diffuser would give about 90% absorption efficiency in 100 ft of bubble plume rise.
DESCRIPTORS: Oxygen Injection, Water Quality Diffusers, Dissolved Oxygen
IDENTIFIERS: Oxygenation
SOURCE: Tetra Tech

Graham, D.S. 1980.
DESTRATIFICATION OF LAKES USING BUBBLE COLUMNS - DISCUSSION.
J. Hydraul. Div., Amer. Soc. Civil Eng. 106:1129-1132.

In this discussion, this writer wishes to evaluate the generality of Kranenburg's results by: (1) Comparing them with selected experiments at larger and smaller scales; and (2) Raising a question of whether the validity of the analysis may be dependent upon the particular experimental configuration employed.
DESCRIPTORS: Destratification, Bubble Column, Mixing, Density
IDENTIFIERS: Induced Mixing, Modeling
SOURCE: Dialog, Author Abstract, Tetra Tech Keywords

Haffner, G.D. 1977.
SPATIAL DISTRIBUTION OF SESTON IN AN ARTIFICALLY MIXED SYSTEM.
Hydrobiologia 54:225-231.

Seston size distribution was determined with a Coulter Counter to investigate seston interaction and its effects on phytoplankton production. Spatial distribution patterns of the non-productive component of the seston were as complex as those commonly associated with algae. Seston might interact influencing production by changes in optical depth, abrasive actions and nutrient adsorption.
DESCRIPTORS: Seston Mixed System, Seston, Phytoplankton Production, Wraysbury Reservoir, Artificial Mixing
IDENTIFIERS: Seston Interaction, Spatial Distribution
SOURCE: Author, Tetra Tech Keywords

Harshbarger, E.D., S. Vigander, G. Hecker. 1975.
MODEL - PROTOTYPE AIR DEMAND FOR GATED TUNNEL DISCHARGES.
Symp. on Reaeration Research, Amer. Soc. Civil Eng. Gatlinburg, Tennessee, October 28-30, 1975. 7 pp.

This paper compares the results of model and prototype air demand tests at Bear Creek dam. An air vent shaft was incorporated into the gated tunnel design, with air vent area about 10 percent of tunnel area for each 150 ft of hydraulic head available. Model measurements included gate opening, water discharge, and air intake for a range of headwater elevations. For both model and prototype, air flow divided by water discharge was inversely correlated with gate opening divided by hydraulic head.
DESCRIPTORS: Reaeration, Gated Tunnel, Air Vent, Dam

IDENTIFIERS: Discharge Aeration, Tunnel Vent
SOURCE: Tetra Tech

Hart, E.D., and S.C. Wilhelms. 1977.
REAERATION TESTS, OUTLET WORKS, BELTZVILLE DAM, POHOPOCO CREEK, PENNSYLVANIA.
Final Rept. No. WES-TR-H-77-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. 44 pp.

Prototype water-quality tests were conducted at Beltzville Dam. The purposes of these tests were to: (a) determine the location and degree of reaeration of flow that occurred as it passed through the outlet works, (b) provide prototype data with which to evaluate the accuracy of the selective withdrawal numerical model, SELECT, and (c) supplement results of hydraulic prototype tests conducted at Beltzville Dam in May 1973. Twelve tests were conducted. Temperature and dissolved oxygen data (vertical profiles) were collected upstream of the dam, at seven stations within the outlet structure, and at one station in the downstream channel. The tests involved various flow rates and various outflow port elevations. The results of these prototype tests showed: (a) the dissolved oxygen content of the release flows was approximately 90 to 95 percent of the saturation level regardless of the dissolved oxygen content of the flow entering the structure or the discharge, and major reaeration occurred within the outlet structure downstream of the water-quality gate; (b) the predictions of the SELECT model were in close agreement with the observed data; and (c) the hydraulic measurements were close to those of the 1973 tests.
DESCRIPTORS: Dams, Downstream Flow, Aeration, Water Flow, Water Quality, Oxygen, Dissolving, Test Methods, Prototypes, Mathematical Models, Mathematical Prediction, Reservoirs, Release, Selection
IDENTIFIERS: Select Computer Program, Beltzville Dam, Pohopoco Creek, Pennsylvania
SOURCE: Dialog

Haynes, R.C. 1973.
SOME ECOLOGICAL EFFECTS OF ARTIFICIAL CIRCULATION ON A SMALL EUTROPHIC LAKE WITH PARTICULAR EMPHASIS ON PHYTOPLANKTON. I. KEZAR LAKE EXPERIMENT, 1968.
Hydrobiologia 43:463-504.

A small eutrophic New Hampshire lake was artifically circulated from July 16 to September 12, 1968. Artificial circulation destratified Kezar Lake completely; the stability of stratification was reduced to zero when the lake became isothermous. Mixing caused an increase in the heat budget. Water transparency also increased after mixing.

Inverse clinograde distributions of Fe, Mn, ammonia-N, CO_2, alkalinity and conductivity were ameliorated after mixing by reoxygenation of stagnant bottom water. The chemical nutrients Ca, Mg, K, Cl, and SiO_2 were little influenced, but a marked increase in total-P occurred when artificial circulation transferred suspended organic detritus into the water column from agitated profundal muds.

The effects of mixing on Na, Cu, Zn, NO_2-N, NO_3-N, organic-N and orthophosphate are also discussed. Most chemical nutrients were distributed isometrically in the water column after mixing. The supply of chemical nutrients was sufficient to support large populations of phytoplankton.

During stagnation a dense bloom of Aphanizomenon flos-aquae occurred. Mixing caused a uniform vertical distribution of this alga and its large population eventually dissipated. The phytoplankton then became dominated by chlorophycean taxa. The variations in chlorophyll-a followed closely changes in phytoplankton abundance. Chlorophyll-a levels are shown to be typical of other eutrophic lakes. Primary production in surface waters decreased markedly subsequent to destratification, but it increased at lower depths in agreement with vertical expansion of the euphotic zone.

DESCRIPTORS: Eutrophic, Phytoplankton, Artificial Circulation, Mixing, Lake Aeration, Primary Production

IDENTIFIERS: Ecological Effects, Lake Phytoplankton, Artificial Circulation

SOURCE: Author, Tetra Tech Keywords

Haynes, R.C. 1975.
SOME ECOLOGICAL EFFECTS OF ARTIFICIAL CIRCULATION ON A SMALL EUTROPHIC LAKE WITH PARTICULAR EMPHASIS ON PHYTOPLANKTON. II. KEZAR LAKE EXPERIMENT, 1969.
Hydrobiologia 46:141-170.

A small eutrophic New Hampshire lake was artificially circulated (mixed) from 28 May to 15 September, 1969 inclusive, to impede the annual bloom of a noxious blue-green alga; yet Aphanizomenon flos-aquae bloomed immediately after mixing was commenced. The bloom collapsed in early July; it was succeeded by heavy growth of predominantly chlorophycean taxa. In an in vitro experiment Aphanizomenon flos-aquae did reattain bloom proportions when the influence of artificial circulation was removed. Other phytoplankton exhibited population pulses only when the dominance of cyanophycean and chlorophycean taxa were in transition. Mixing maintained uniform vertical populations of all phytoplankton. Changes in water transparency attended fluctuations in phytoplankton abundance.

An isothermic condition was maintained over the test period, which increased the lake's heat budget, and most chemical nutrients were distributed isometrically in the water column. Increased concentrations were exhibited by Ca, Cl, Cu, K, Mg, SiO_2 and Zn. Sodium was not affected by mixing. Levels of Fe, Mn, Zn, phosphate and ammonia, nitrate, and organic nitrogen were influenced by phytoplankton. Mixing could not maintain orthograde profiles of dissolved O_2 and CO_2 when dense populations of phytoplankton prevailed.

Variations in chlorophyll-a followed closely changes in phytoplankton abundance. Its degradation to phaeo-pigments appeared to be less for a bloom of Aphanizomenon flos-aquae than during dense

growth of chlorophycean taxa. Rates of photosynthesis were considerably greater when the latter algae were predominant. Extracellular release of organic carbon usually increased with depth; it amounted to 19.4 percent of the total carbon fixed in the euphotic zone.
DESCRIPTORS: Mixing, Aeration, Eutrophic, Blue-green Algae, Water Quality
IDENTIFIERS: Artificial Circulation, Aeration
SOURCE: Author, Tetra Tech Keywords

Henderson-Sellers, B. 1978.
FORCED PLUMES IN A STRATIFIED RESERVOIR.
J. Hydraul. Div., Amer. Soc. Civil Eng. 104:487-501.

A comprehensive two or three-dimensional model for a forced plume is described in which there are no restrictions necessary in the choice of cross-sectional velocity or density profiles, angle of efflux, values of initial momentum and buoyancy fluxes or the ambient stratification. The introduction of such an inflow into a reservoir is shown to affect the stratification and if 'jetting' is undertaken, destratification results.
DESCRIPTORS: Lakes, Mathematical Models, Stratification, Water Temperature, Chemical Plumes
IDENTIFIERS: Water Quality, Jetting
SOURCE: Author, Tetra Tech Keywords

Hess, L. 1974.
THE SUMMER CATCH, VERTICAL DISTRIBUTION AND FEEDING HABITS OF TROUT IN SPRUCE KNOB LAKE.
Proc. W. Virginia Acad. Sci. 46:255-264.

Spruce Knob Lake is being studied in an attempt to verify and improve poor summer trout fishing. A 1973 creel census indicated that from mid-July until mid-October, 3,191 anglers fished 7,650 (7,097-8,203 95% C.I.) hours and caught 1,050 (854-2,246 95% C.I.) trout. Trout fishing success was poorest in midsummer, when the catch rate was 0.03 trout/hr. but increased to 0.32 trout/hr. for early fall anglers. The improved fall fishing does not reflect additional stocking but rather is due to increased trout feeding.

A study of the feeding habits of trout in the lake revealed that during the summer trout fed only one quarter as much as during the fall. The reason for their poor summer feeding is lack of suitable trout habitat. The dissolved oxygen content of the hypolimnion was far below that acceptable for trout and epilimnion temperatures reached the lethal threshold. Vertical distribution of trout was most restricted in late August and early September when no fish was caught below a depth of 2 m. Trout adapted to the adverse temperature conditions by moving into deeper waters during the day and shallower waters at night when water temperatures decreased.

Hypolimnion aeration of Spruce Knob Lake should improve summer trout fishing by increasing dissolved oxygen concentrations in the cooler strata of the lake.

DESCRIPTORS: Trout, Feeding Habits, Summer Catch, Vertical Distribution, Temperature Gradients
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Author, Tetra Tech Keywords

Hess, L. 1975.
THE EFFECT OF THE 1st YEAR OF ARTIFICIAL HYPOLIMNION AERATION ON OXYGEN TEMPERATURE AND THE DEPTH DISTRIBUTION OF RAINBOW TROUT SALMO-GAIRDNERI IN SPRUCE KNOB LAKE, WEST VIRGINIA, USA.
Proc. W. Virginia Acad. Sci. 47:176-183.

A new hypolimnion aerator was tried at Spruce Knob Lake, W. Va. Artificial aeration began on July 15, 1974 and continued intermittently until September 20, 1974. After artificial aeration, average hypolimnetic oxygen concentrations were 2.7 mg/l higher (3.1 times greater) and average hypolimnetic temperatures 0.7^{0} C higher than those observed the preceding summer without aeration. Aeration had no discernible effect on the vertical distribution of rainbow trout (Salmo gairdneri Richardson). Future plans call for modifying the aeration system to increase dissolved oxygen concentrations and stimulate greater utilization of hypolimnetic water by trout.

DESCRIPTORS: Aerator, Season
IDENTIFIERS: Hypolimnion Aeration, Artificial Aeration
SOURCE: Dialog, Author Abstract, Tetra Tech Identifiers

Hess, L. 1977.
LAKE DESTRATIFICATION INVESTIGATIONS. JOB 1-3: LAKE AERATION JUNE 1, 1972 TO JUNE 30, 1977.
Final Report, West Virginia Department of Natural Resources. D-J Project F-19-R.

Artificial hypolimnion aeration of Spruce Knob Lake was undertaken in 1974 and 1975. Mechanical aeration during 1975 raised dissolved oxygen concentrations and reduced changes in temperature regimes, but circulated less water than did compressed air aeration in 1974. In general hypolimnetic chemical conditions improved, but had little effect on zooplankton, benthos, or crayfish abundance. However, trout fed heavier during aeration. Significantly greater numbers of trout were found in hypolimnetic waters in July during aeration. Vertical distribution of trout during June showed less change during aeration because surface temperatures and bottom oxygen concentrations were similar to pre-aeration levels. Aeration equipment was unable to maintain satisfactory hypolimnetic dissolved oxygen concentrations, resulting in similar before and after vertical distribution of trout during August. Aeration with compressed air in 1974 did not significantly change the summer catch rates, apparently because of unsatisfactory hypolimnetic water quality, but mechanical aeration in 1975 increased July-August catch rates four-fold over those observed before aeration to an average of 0.11 trout/hr.

DESCRIPTORS: Hypolimnion, Mixing, Circulation, Aeration, Lake, Limnology, Pre-aeration

IDENTIFIERS: Destratification, Artificial Aeration, Aeration Studies
SOURCE: Author, Tetra Tech Keywords

Hickel, B. 1978.
PHYTOPLANKTON-SUKZESSION IM GREBINER SEE WAHREND EINER KUNSTLICHEN BELUFTUNG DES HYPOLIMNIONS [PHYTOPLANKTON SUCCESSION IN THE GREBINER SEE DURING ARTIFICIAL AERATION OF THE HYPOLIMNION].
Arch. Hydrobiol. 82:216-230.

The composition of the phytoplankton and the succession of species was studied for one year in the eutrophic Grebiner See (East-Holstein) in connection with the restoration of this lake by Ohle.

Diatoms were dominant in spring and autumn, Chlorophyceae in summer and Peridineae in late summer. Cyanophyceae were represented by several species, however, without forming blooms. Aphanizomenon flos-aquae was the only blue-green alga which was more abundant in late summer. Populations of desmids - normally not important in the lakes of East-Holstein - were relatively abundant during the aeration in Grebiner See. Besides Staurastrum pseudopelagicum and St. luetkemuelleri, which have not been observed previously in the lakes of the area, the species found are distributed in eutrophic lakes.

DESCRIPTORS: Artificial Aeration, Hypolimnion, Eutrophic Lakes, Phytoplankton, Succession (Ecological)
IDENTIFIERS: Check Lists, Annual Variations, Aphanizomenon flos-aquae, Staurastrum
SOURCE: Author, Dialog Keywords

Hise, R.E. 1975.
A MODEL OF GAS DISSOLUTION IN WATER.
Symp. on Reaeration Research, Amer. Soc. Civ. Eng., Gatlinburg, Tennessee, October 28-30, 1975. 15 pp.

Analysis of gas bubble dissolution has shown that diffusers releasing bubbles smaller than 1-mm diameter are highly desirable for efficient gas dissolution in a specified depth of liquid.

Bubble rise velocity and mass transfer film coefficients have been compiled for bubbles to 1 cm in diameter for ordinary, distilled, and pure water. The effect of the bubble plume rising above a diffuser has also 'een considered.

DESCRIPTORS: Bubble, Dissolution, Oxygen, Plume, Diffuser
IDENTIFIERS: Reaeration
SOURCE: Author, Tetra Tech Identifiers

Hoopes, J.A., P.L. Monkmeyer, N.V. Ionescu, K.V. Henkel, V. Alavian. 1979.
SELECTIVE WITHDRAWAL AND HEATED WATER DISCHARGE: INFLUENCE ON THE WATER QUALITY OF LAKES AND RESERVOIRS. PART II - INDUCED MIXING WITH SUBMERGED, HEATED WATER DISCHARGE.

Technical Report WIS/WRC-79/04. Wisconsin Univ., Madison, Wisconsin. 98 pp.

Various methods have been proposed to improve the water quality of stratified lakes and reservoirs. This report presents a field and theoretical investigation of the induced, vertical mixing in a temperature-stratified impoundment resulting from the submerged discharge of heated water. This work shows that a subsurface, heated water discharge can induce vertical mixing of a stratified impoundment. The feasibility of considerations in using this method of mixing along with relations and procedures for applying the results of this study to an impoundment are presented. A numerical model of an impoundment's temperature structure and changes thereto, resulting from a submerged, vertical, heated water discharge and/or atmospheric energy exchange is presented. The model is in good agreement with observations of the natural temperature distribution (no heated water discharge) in two lakes; model predictions show the changes in the "natural" temperature distribution for one lake induced by a submerged, heated water discharge.

DESCRIPTORS: Aeration, Lakes, Reservoirs, Water Pollution Control, Stratification, Mixing, Pumping, Hydraulics, Mathematical Models, Temperature, Water Flow, Heat Transfer, Momentum, Thermal Pollution, Field Tests, Lake Mendota, Wisconsin

IDENTIFIERS: Destratification, Thermal Stratification

SOURCE: Dialog

Howard, R.G. 1972.
RESERVOIR DESTRATIFICATION IMPROVES WATER QUALITY.
U.S. Reclamation Bureau, *Reclamation Era* 58:6-7.

To destratify the upper waters of Lake Casitas, California, air is being injected into the reservoir at a depth of 140 ft.

Dissolved oxygen is present at depths up to 120 ft throughout the summer, as compared to only 25 ft before aeration. The air injection program has improved a trout fishery. Aeration is less expensive than the copper sulfate treatments previously required to control algal growth. Less chlorine is now necessary for efficient water treatment.

DESCRIPTORS: Mixing, Aeration, Water Quality, Water Treatment

IDENTIFIERS: Partial Destratification, Diffused Air

SOURCE: Tetra Tech

Ivakhnenko, A.G., and N.V. Gulyan. 1972.
A MATHEMATICAL MODEL OF ARTIFICIAL AERATION OF A POND.
Hydrobiol. J. 8:59-64.

The data from pond aeration experiments at the Tyasmin facility were used to construct a mathematical model of the process. A special form of regression analysis called the "group method of data handling" was employed for this purpose. The aim was to derive a set of theoretical equations describing the oxygen concentration in the ponds as a function of the amount of air bubbled through if some information about the condition of the water in the last 8 hours is available.

Since the method has been fully described in the literature, we have provided only the essential data used to devise the equations and discussed some aspects of the selection of the optimum model. The final result with an appraisal of its accuracy is also given.
DESCRIPTORS: Mathematical Model, Aeration, Pond
IDENTIFIERS: Artificial Aeration
SOURCE: Author, Tetra Tech Keywords

Jennett, J.C., R.H. Clark, and C.M. Pai. 1972.
HYPOLIMNION REAERATION OF SMALL RESERVOIRS AND LAKES.
Completion report. Missouri Water Resources Research Center, Rolla, Missouri. 100 pp.

The oxygen transfer rates and the oxygen transfer efficiencies of different types of aerators were studied in lakes, and the number of diffusers required for hypolimnion aeration was determined. The types of aerators included a cylindrical stone diffuser, a spherical stone diffuser, and 2 ceramic diffusers which differed in pore size. The oxygen transfer rates and efficiencies of the ceramic diffusers were greater than those of the stone diffusers. For a given type of diffuser, a higher transfer rate was generated with pure oxygen than with air. Hypolimnion aeration of Bray's Lake, Missouri, was feasible using the diffusers studied.
DESCRIPTORS: Aeration, Lakes, Stratification, Dissolved Gases, Oxygen, Mass Transfer, Diffusion, Diffusers, Oxygenation, Equipment, Bray's Lake, Missouri, Efficiency, Water Pollution
IDENTIFIERS: Hypolimnion, Reaeration, OWRR
SOURCE: Dialog

Johnson, D., and J.M. Davis. 1980.
RESERVOIR MIXING TECHNIQUES - RECENT EXPERIENCE IN THE UK.
pp. 140-145. In: Restoration of Lakes and Inland Waters, EPA 440/5-81-010, U. S. Environmental Protection Agency, Washington, D. C.

The United Kingdom has about 180 impounding and pumped storage reservoirs of sufficient size and location which are likely to stratify thermally. Of these at least 30 have, or plan to install, a destratification system. The two systems most commonly used are submerged jetted inlets for pumped storage reservoirs and perforated-pipe air-mixing systems for impounding reservoirs. When operating, these systems maintain temperature differences between surface and bottom waters of $1\text{-}3^{o}$ C compared with differences of $8\text{-}9^{o}$ C under stratified conditions. The chemical quality of the water is also maintained at a higher standard.
DESCRIPTORS: Reservoirs, Destratification, Jetted Inlets, Diffused Air, Water Quality
IDENTIFIERS: Destratification, Water Jets
SOURCE: Author, Tetra Tech Keywords

Johnson, P.L. 1980.
THE INFLUENCE OF AIR FLOW RATE ON LINE DIFFUSER EFFICIENCY AND IMPOUNDMENT IMPACT.
Paper presented at Amer. Soc. Civil Eng. meeting, Minneapolis, Minnesota.

This paper explores the relationship between the air flow rate per foot of diffuser and the efficiency of the destratification that results. Field data were collected at Lake Casitas to be used in developing useful diffuser design criteria. A four-fold variation of air flow rate per unit diffuser length results in little change in destratification efficiency and oxygenation efficiency. At a given air flow rate, the bubble curtain from a line diffuser was more efficient than a system of four point source diffusers. Diffuser efficiencies can be weighed against the profiles as a diffuser design criteria.

DESCRIPTORS: Mixing, Aeration, Dissolved Oxygen, Temperature
IDENTIFIERS: Destratification, Air Diffusers
SOURCE: Tetra Tech

Johnson, P.L., and D.L. King. 1975.
PREDICTION OF DISSOLVED GAS AT HYDRAULIC STRUCTURES.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975.

Hydraulic structures such as stilling basins present an opportunity for oxygenation of oxygen-deficient releases from reservoirs while at the same time posing a potential threat of supersaturation of dissolved gas. This paper presents a proposed method of analysis leading to prediction of the increase or decrease of dissolved gas passing through a hydraulic structure. An equation is presented with coefficients evaluated by analysis of prototype data.

DESCRIPTORS: Aeration, Oxygenation, Research, Water Quality, Hydraulics
IDENTIFIERS: Oxygenation, Water Quality
SOURCE: Author, Tetra Tech Identifiers

Kalnin'sh, A.Y., R.E. Reyzin'sh, and O.Y. Vitols. 1973.
USE OF AERATION TO PRESERVE THE PURITY OF RIVERS AND OTHER BODIES OF WATERS.
Sov. Hydrol. 6:548-551.

Thirteen aerators have been put into operation in August 1971 on the reservoir of the Slokenbek mill on the Slocene River below Tukums City (Latvian SSR), supplying more than 4 kg of oxygen per kW-hour of electric power, under standard conditions (i.e., in pure water completely devoid of oxygen at a temperature of 20^{o} C). Whereas the content of organic substances averaged 67.2% and that of mineral substances 32.8% in the upper layer of bottom silt (at a depth to 10 cm) at the beginning of the flood period of 1971, a year later organic matter decreased to 25.2% under the same conditions after half a year of aeration, and to 11% after the next 6 months. Since the amount of mineral substances apparently remained the same as before, the amount of organic substances in the sediment

decreased by a factor of 12. Systematic aeration of entire river basins would be more economical, because, on the whole, the rivers of the Soviet Union and even those of the most populated regions still have a large self-purification capacity. Self-purification breaks down only at individual points.
DESCRIPTORS: Water Pollution, Control, Water Resources
IDENTIFIERS: Aeration, Reservoir, Water Pollution
SOURCE: Dialog, Tetra Tech Identifiers

Karasik, V.M., Yu., N. Krivenko, and I.I. Stovbon. 1972.
STUDY OF THE OPERATION OF WATER AERATORS.
Hydrobiol. J. 8:45-48.

This article reports briefly on the results of laboratory and field tests of the bubbler and ejector methods of aerating water, started in 1970 by the Institute of Fluid Flow jointly with the Institute of Hydrobiology, Ukrainian Academy of Sciences.
DESCRIPTORS: Water, Aeration, Aerators
IDENTIFIERS: Bubble-Cap Aerators
SOURCE: Author, Tetra Tech Keywords

Keto, J., and P. Seppanen. 1973.
LAKE TUUSULA DESTRATIFICATION AND AERATION TEST, WINTER 1972/73.
Aqua Fennica (1973):126-136.

Lake Tuusula receives sewage and farming effluents. In late winter, dissolved oxygen concentrations reach critically low levels; e.g., less than 1 mg/l in water at 1-m depth. The 1972/73 test involved destratification by air released from an array of 56 disk aerators suspended from five rafts. The equipment design and costs are described.

Aeration increased the oxygen content of the lake significantly, but also caused a turbidity increase during rapid circulation. Treatment appeared to decrease total phosphorus and pH. Total nitrogen was higher during the test winter than during previous control years.
DESCRIPTORS: Mixing, Diffused Air, Water Quality, Phosphorus, Nitrogen, Lakes
IDENTIFIERS: Destratification, Aeration
SOURCE: Tetra Tech

Khudenko, B.M. 1979.
POSTAERATION OF WASTEWATER.
J. Environ. Eng. Div., Amer. Soc. Civil Eng. 105:297-307.

Recommendations for the design of pneumatic and mechanical aerators and weirs for postaeration are presented. The recommendations are based on experimental results from pilot plant scale and full scale installations. Recommended alternatives are either a series of baffled reservoirs for pneumatic or mechanical aeration or a series of tooth-shaped weirs or openings. Baffling results in a reduction of both required vessel volume and energy

consumed. Recommended design parameters for aeration systems are different than those usually accepted for the activated sludge process, for example, intensities of pneumatic aeration as high as 50 to 100 m^3 m^{-2} hr^{-1}, with aerators covering up 50% to 100% of the tank bottom. Tooth-shaped weirs or openings produce the largest increase in aeration of all the configurations examined, owing to the high degree of nappe conversion.
DESCRIPTORS: Wastewater, Water Treatment, Aeration, Weirs
IDENTIFIERS: Wastewater Treatment, Aerators
SOURCE: Dialog

Klapper, H. 1976.
DIE KUNSTLICHE TIEFENWASSER BELUFTUNG AND IHR EINFLUSS AUF DEN STOFFHAUSHALT EINER NAHRSTOFFREICHEN TALSPERRE [ARTIFICIAL DEEPWATER AERATION AND ITS INFLUENCE ON THE MATERIALS BALANCE IN A NUTRIENT RICH RESERVOIR].
Limnologica 10:607-616.

In a large research project, the effects of pump output and the ventilation jet of compressed air were considered. Through ventilation of deep waters, the hypolimnion of Rappbode-Vorsperre reservoir was maintained in an aerobic state without destruction of thermal stratification. H_2S hardly appeared; Mn content was descreased significantly. It was not possible to achieve a reduction of phosphate; the iron-rich reservoir sediments tie up phosphorus even under anaerobic conditions.
DESCRIPTORS: Hypolimnion, Reservoir, Diffused Air, Water Quality
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Tetra Tech Translation of Summary; Tetra Tech Keywords

Knapp, G.L. 1973.
AERATION OF NATURAL WATERS: A BIBLIOGRAPHY.
Report No. WRSIC-73-206, Office of Water Resources Research, Washington, D.C.

The report, contains 240 abstracts on improving water quality by artificial aeration. It is another in a series of planned bibliographies in water resources to be produced from the information base comprising Selected Water Resources Abstracts (SWRA). At the time of search for this bibliography, the data base had 53,230 abstracts covering SWRA through February 15, 1973 (Volume 6, Number 4). Author and subject indexes are included.
DESCRIPTORS: Aeration, Water Quality, Bibliographies, Aeration, Entrainment, Algae, Biochemical Oxygen Demand, Cavitation, Dissolved Gases, Oxygen, Estuaries, Hydraulic Models, Lakes, Streams, Mathematical Models, Mixing, Open Channel Flow, Optimization, Oxygenation, Reservoirs, Rivers, Soils, Stratification, Turbulence, Water Chemistry, Water Pollution, Temperature, Water Treatment
IDENTIFIERS: Eutrophication, Path of Pollutants, Thermal Pollution, Water Pollution Control
SOURCE: Dialog

Kothandaraman, V., D. Roseboom, and R.L. Evans. 1979.
PILOT LAKE RESTORATION INVESTIGATIONS - AERATION AND DESTRATIFICATION IN LAKE CATHERINE.
Illinois State Water Survey, Urbana. Illinois Inst. of Natural Resources, Chicago, Illinois. Final Report. 58 pp.

An aeration destratification system developed by the Aquatic Environmental Control Company (AECC) was installed in Lake Catherine, a part of the Fox Chain of Lakes, on May 18, 1978. The system consists of a multistage deep well pump, AECC aeration unit, air hoses, and a variable pitch mounting skid to support the aerator on the lake bottom. The AECC system was selected over other aeration systems because of its quiet operation and the reliability of deep well pumps. The only obstruction on the lake surface is a lighted warning buoy which supports the two air hoses. Modifications were required for satisfactory operation which was achieved on July 6, 1978.

DESCRIPTORS: Aeration, Lake Catherine, Water Pollution Control, Stratification, Pumps, Air Flow, Aerators, Buoys, Warning Systems, Luminaires, Pipes (Tubes), Illinois, Fox Lakes
IDENTIFIERS: Destratification
SOURCE: Dialog

Kranenburg, C. 1979.
DESTRATIFICATION OF LAKES USING BUBBLE COLUMNS.
J. Hydraul. Div., Amer. Soc. Civil Eng. 105:333-349.

Mathematical and physical modeling makes possible quantitative predictions as regards the destratification process brought about by the local injection of air at the bottom of a thermally stratified lake or reservoir. The mathematical model distinguished between a near field and a far field. Mixing of epilimnion water and hypolimnion water takes place in the near field. The mixing water is accumulated in the far field as an interlayer between epilimnion and hypolimnion. The influence of wind on the mixing is not considered. The agreement between theory and model experiments is satisfactory, but further measurements in nature are needed. Increasing the number of injection points is an effective means to speed up the destratification process. Increasing the air flow rate, however, is not.

DESCRIPTORS: Stratification, Lakes, Mathematical Models, Water Mixing
IDENTIFIERS: Hydraulics, Plumes (Aquatic), Water Quality, Reservoirs
SOURCE: Dialog

LaBaugh, J.W. 1979.
CHLOROPHYLL PREDICTION MODELS AND CHANGES IN ASSIMILATION NUMBERS IN SPRUCE KNOB LAKE, WEST VIRGINIA.
Arch. Hydrobiol. 87:178-197.

Values of P_{max}, chlorophyll concentrations, and assimilation numbers were obtained during a limnological investigation from July

14, 1973, to September 20, 1975, at Spruce Knob Lake, West Virginia. The impoundment was destratified between May 31, 1975, and June 14, interrupting summer stratification. Mean summer chlorophyll concentrations were significantly lower in 1975 (133.0 mg/m^3, 1974; 26.0 mg/m^3, 1975). Assimilation numbers were significantly higher in 1975 (0.70 mgC/mg chlorophyll/hr., 1974; 1.45 mgC/mg chlorophyll/hr., 1975). There was no significant difference between P_{max} or total phosphorus means for the summer periods. There were significant differences in total inorganic carbon means during the mid-July to autumnal overturn periods (2.04 mg/l, 1975; 1.42 mg/l, 1974; 0.77 mg/l, 1973). Regression analysis indicated that chlorophyll concentrations demonstrated a significant positive relationship with total phosphorus only in the two late periods that had the lower total inorganic carbon concentrations. Several literature phosphorus-chlorophyll models applied to Spruce Knob Lake data predicted mean summer chlorophyll levels with varying degrees of success; the best predictions were obtained with models incorporating hydrologic regime effects. Temperature and chlorophyll were the most important variables influencing P_{max} during the investigation. Assimilation numbers demonstrated a significant positive relationship with temperature and a significant negative relationship with chlorophyll on a yearly basis. Summer assimilation numbers were strongly influenced by P_{max} when chlorophyll levels remained below 50 mg/m^3.
DESCRIPTORS: Limnology, Chlorophyll, Primary Production, Water Chemistry, Temperature, Assimilation Number
IDENTIFIERS: Destratification
SOURCE: Author, Tetra Tech Keywords

LaBaugh, J.W. 1980.
WATER CHEMISTRY CHANGES DURING ARTIFICIAL AERATION OF SPRUCE KNOB LAKE, WEST VIRGINIA.
Hydrobiologia 70:201-216.

The water mass below 3.5 m in Spruce Knob Lake was artificially aerated with a modified full lift aerator during two consecutive summers (1974 and 1975) of an investigation that began in July of 1973 and ended in September, 1975. Artificial aeration increased water temperature below 3.5 m without causing destratification. Several chemical parameters were significantly affected by artificial aeration, especially from July to autumnal overturn in 1974 and 1975. Below 3.5 m, total inorganic carbon, total alkalinity, nitrite, soluble reactive phosphorus, and total phosphorus were lower during aeration than in the summer of no aeration (1973). Although artificial aeration lowered soluble reactive and total phosphorus, there was no significant impact on the phosphorus budget of the impoundment. In 1975, continuous aeration from vernal overturn to autumnal overturn resulted in higher nitrate concentrations below 3.5 m than in the preceding summers. Lower pH values encountered through the whole water column in 1975 followed a brief isothermal interruption of summer stratification in early June. There was no direct effect of

artificial aeration on either temperature or water chemistry parameters in the epilimnion. Significantly lower chlorophyll concentrations observed in 1975 were related to destratification in June. Primary production was unaffected by aeration.
DESCRIPTORS: Artificial Aeration, Water Chemistry, Chlorophyll, Phosphorus Budget, Reservoir
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Author, Tetra Tech Keywords

Lackey, R.T. 1972.
RESPONSE OF PHYSICAL AND CHEMICAL PARAMETERS TO ELIMINATING THERMAL STRATIFICATION IN A RESERVOIR.
Water Resour. Bull. 8:589-599.

The effects of maintaining a 19-ha Colorado montane reservoir in a thermally destratified condition for one year were evaluated. Water temperatures were kept nearly vertical and horizontally isothermal throughout the year. The weighted mean temperature of the lake was 1-4^{o} C colder in winter and 1-2^{o} C warmer in summer than normal. Deep water in summer was up to 6^{o} C warmer than hypolimnion temperatures, but summer surface temperature was unaltered.
DESCRIPTORS: Reservoirs, Thermal Stratification
IDENTIFIERS: Destratification, Hypolimnion Temperatures
SOURCE: Dialog

Lackey, R.T. 1973a.
ARTIFICIAL RESERVOIR DESTRATIFICATION EFFECTS ON PHYTOPLANKTON.
J. Water Pollut. Control Fed. 45:668-673.

A 19-ha Colorado montane reservoir was kept thermally destratified by continuous aeration for 1 yr. Total phytoplankton abundance was reduced, but phyla varied in their response. Vertical distribution of phytoplankton was not affected by destratification.
DESCRIPTORS: Reservoirs, Thermal Stratification, Water Bacteriology, Water Treatment, Aeration
IDENTIFIERS: Phytoplankton
SOURCE: Dialog

Lackey, R.T. 1973b.
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON ZOOPLANKTON IN PARVIN LAKE, COLORADO.
Trans. Am. Fish. Soc. 102:450-452.

Parvin Lake, Colorado, a 19-ha montane reservoir, was artificially destratified for 1 year. Abundance of cladocerans (collectively) and <u>Daphnia schødleri</u> was lower during destratification. Abundance of rotifers (collectively) was lower during winter months and higher during summer months of the destratification year. Abundance of copepods (mainly <u>Diaptomus</u> spp.) was not statistically different during destratification. Depth distribution of zooplankton was generally

unaffected, but Diaptomus spp. tended to occur in deeper water during the destratification year.
DESCRIPTORS: Lake Destratification, Zooplankton, Abundance
IDENTIFIERS: Artificial Destratification
SOURCE: Author, Tetra Tech Keywords

Lackey, R.T. 1973c.
BOTTOM FAUNA CHANGES DURING ARTIFICIAL RESERVOIR DESTRATIFICATION.
Water Res. 7:1349-1356.
A 19-ha montane reservoir was kept vertically isothermal by aeration all year around. Four macrobenthic species were abundant during the study. Hyallella significantly increased in abundance in shallow water during destratification.
DESCRIPTORS: Reservoirs, Thermal Stratification, Water Bacteriology
IDENTIFIERS: Bottom Fauna Changes
SOURCE: Dialog

Lauer, W.C. 1978.
DENVER'S SEASONAL ODOR PROBLEM: AN UNUSUAL, COST-FREE SOLUTION.
J. Amer. Water Works Assoc. 577-580.
Artificial destratification by lowering the elevation of the terminal reservoir supplying its main treatment plant is reported to be Denver's simple - and serendipitous - solution to a long-standing seasonal odor problem. Development of odors in thermally stratified reservoirs was caused by chemical as well as biological factors - dissolved oxygen, pH, carbon dioxide, plankton growth, and bacterial activity - that are influenced by the formation of the thermal layers.
DESCRIPTORS: Odor Control, Reservoirs, Thermal Stratification, Water Pollution, Control
IDENTIFIERS: Destratification
SOURCE: Dialog

Leach, L.E. 1974.
RESERVOIR AERATION TECHNIQUES FOR WATER QUALITY CONTROL.
ASCE Natl. Water Resour. Eng. Meet, Los Angeles, CA, Jan 21-25, 1974. New York. 32 pp.
This presentation is intended as an overview of artificial reservoir aeration techniques. Included is a review of the characteristics of systems developed for complete reservoir destratification, hydro-power and low-level release aeration, and hypolimnion aeration of stratified reservoir with the objective of maintaining temperature stratification while oxygenating the bottom anaerobic zone. This paper also describes aeration effects on several chemical and biological parameters.
DESCRIPTORS: Water Treatment, Aeration, Reservoirs, Thermal Stratification
IDENTIFIERS: Water Quality Control
SOURCE: Dialog

Lorenzen, M.W. 1977.
AERATION/CIRCULATION KEEPS ALGAL BLOOMS IN CHECK.
Water Wastes Eng. 14:88-92.

Lake eutrophication may be controlled by inducing water flow. Mechanical systems can pump water from bottom to top or vice versa. Air diffusers have also been used to provide vertical mixing. An analysis of the relationships between air flow and water flow as well as the effects of various mixing levels on the resulting temperature and algal profiles are described. A summary of lake characteristics and the air flow required to provide mixing that results in small variations in vertical algal concentrations and temperatures is tabulated. The choice, design and layout of air diffuser systems is described.

DESCRIPTORS: Algal Blooms, Water Mixing, Eutrophication, Water Quality Control
IDENTIFIERS: Lakes, Control, Water Circulation, Lake, Bloom
SOURCE: Dialog

Lorenzen, M.W., and A.W. Fast. 1977.
A GUIDE TO AERATION/CIRCULATION TECHNIQUES FOR LAKE MANAGEMENT.
Ecol. Res. Ser. EPA-600/3-77-004. U.S. Environ. Prot. Agency.

The application of aeration/circulation techniques to lakes are reviewed from a theoretical and practical viewpoint. The effect of destratification on algal production is related to the mixed depth with the use of a mathematical model. Procedures are given to determine air required to mix lakes of different sizes and shapes. It was found that approximately 30 scfm of air per 1,000,000 sq ft of lake surface area can be used. Hypolimnetic aeration systems that have been used are described in detail. Procedures for design are given.

DESCRIPTORS: Aeration, Circulation, Stratification, Lakes, Algae, Mathematical Models, Requirements, Mixing, Size Determination, Reservoirs, Plant Growth, Design, Systems Engineering, Aerators, California
IDENTIFIERS: Destratification, Hypolimnion, Eutrophication
SOURCE: Dialog

Lorenzen, M.W., and R. Mitchell. 1973.
THEORETICAL EFFECTS OF ARTIFICIAL DESTRATIFICATION ON ALGAL PRODUCTION IN IMPOUNDMENTS.
Environ. Sci. Technol. 7:939-944.

Artificial mixing is used in the management of eutrophic lakes and reservoirs. Theoretical models of phytoplankton production are reviewed and a model for application to mixed impoundments is derived. The model considers both nutrient depletion and the balance between photosynthesis and respiration as potential biomass limiting factors.

DESCRIPTORS: Reservoirs, Thermal Stratification, Lakes, Water Pollution, Mathematical Models
IDENTIFIERS: Algal Production, Impoundments
SOURCE: Dialog

Lorenzen, M.W., and R. Mitchell. 1975.
AN EVALUATION OF ARTIFICIAL DESTRATIFICATION FOR CONTROL OF ALGAL BLOOMS.
J. Amer. Water Works Assoc. 67:373-376.

Artificial destratification of Kezar Lake in 1968, 1969, and 1970 did not increase algal biomass; in fact, total peak biomass was somewhat lower during the period of continuous aeration. Because the total biomass was reduced at the same time the depth of the mixed layer was increased, the concentration of algal cells was significantly reduced. This result is qualitatively consistent with model predictions. Only in 1968 when the lake was thermally stratified did cell counts approach the value indicated by laboratory tests for nutrient limited biomass. Apparently, algae were not able to utilize the available nutrients when artificially mixed. This result would suggest that the peak biomass was limited by available light even in this shallow (3-m) lake.

Artificial destratification for the control of algal blooms can be a successful and inexpensive technique. However, the suitability of a lake should be evaluated prior to implementation. The approach to evaluation described here has been simplified in order to provide a general guide for water-quality management decision-making. This approach provides a rational framework for evaluating the effect artificial mixing will have on the magnitude of algal blooms.

It is important to note that the scope of this article has been limited to the effects on peak algal biomass and has not included consideration of temperature changes, algal species changes, long-term effects on nutrient budgets, or the exact timing of blooms.

The Kezar Lake example illustrates the procedures and type of information that can be gained from the analysis described herein. However, further evaluation of a number of different lakes with greater average depths is needed in order to fully evaluate the usefulness of the model.

DESCRIPTORS: Destratification, Water Quality, Mixing, Nutrients, Algal Blooms, Aeration, Lake
IDENTIFIERS: Artificial Aeration, Artificial Destratification
SOURCE: Author, Tetra Tech Keywords

Lossow, K., A. Sikorowa, H. Drozd, A. Wuchowa, H. Nejranowska, M. Sobierajska, J. Widuto, and I. Zmyslowska. 1975.
RESULTS OF RESEARCH ON THE INFLUENCE OF AERATION ON THE PHYSICO-CHEMICAL SYSTEMS AND BIOLOGICAL COMPLEXES IN THE STARODWORSKIE LAKE OBTAINED HITHERTO.
Pol. Arch. Hydrobiol. 22:195-216.

Artificial aeration of hypolimnion waters has been carried out with diffuse air injection system in the Starodworskie Lake since

1972. The lake is small (7 ha) but very deep (23 m). Evident changes in the physico-chemical systems and biological complexes were noticed in the first year of the experiment. The following phenomena were observed: liquidation of thermocline, increase of the oxygen amount in the over-bottom layer and its decrease in the surface strata, increase of temperature in the water mass, speeding-up of the organic substances decay, intensification of nitrification processes and precipitation of phosphorus into the bottom sediments. Shortening of the period of intensive primary production and increase of production contribution from the summer period were also observed. Changes of components in zooplankton were recorded. The average amount of the bottom fauna went up from two to ten times yearly. Considerable utility of the method for ice-melting and preventing the appearance of too much oxygen in polluted, deep lakes was confirmed.
DESCRIPTORS: Hypolimnion, Diffused Air, Water Quality Phytoplankton, Primary Production, Zooplankton, Benthos
IDENTIFIERS: Hypolimnetic Aeration, Lake Effects
SOURCE: Author, Tetra Tech Keywords

Malueg, K.W., J.R. Tilstra, D.W. Schults, and C.F. Powers. 1973.
EFFECT OF INDUCED AERATION ON STRATIFICATION AND EUTROPHICATION PROCESSES IN AN OREGON FARM POND.
Geophys. Monogr. Ser. 17:578-587.

Thermal destratification in the test section occurred within 3 days following aeration. Dissolved oxygen concentration in the control section remained highly stratified, the range being from 16.1 mg/l in the surface waters to undetectable at deeper levels. Dissolved oxygen in the test section was homogenous at 5.1 mg/l after 3 days of destratification, decreased 1 week later, and then increased to about 7 mg/l. The pH ranged from 6.4 to 7.2 in the test section, whereas the values ranged from 6.2 to 9.6 in the control. The total phosphate concentrations of the test and control sections did not differ significantly. Orthophosphate concentrations increased in the test section following destratification but decreased after several weeks. No such increase occurred in the control. Little difference in nitrogen concentrations occurred between sections. Specific conductance ranged from 90 to 140 umhos^{-1}/cm at 25^{o} C in both sections, total alkalinity ranged from 30 to 50 mg/l, and total inorganic carbon ranged from 12 to 20 mg/l. The transparency in the test section was almost always greater than that in the control section. The aerated section had generally uniform concentrations of chlorophyll a, averaging about 20 mg/m^{3}, whereas the control section had greater concnetrations in the upper waters, the maximum concnetration being 110 mg/m^{3}. Total numbers of phytoplankton declined in the aerated section following destratification. Later a large population of the green flagellate, *Trachelomonas*, developed and predominated at all depths. In the control section, *Trachelomonas* and a blue green, *Anabaena*, occurred in bloom proportions. Destratification vastly enhanced the esthetic appearance of the aerated section relative to that of the control.

DESCRIPTORS: Phytoplankton, Aeration, Eutrophication, Stratification, Pond
IDENTIFIERS: Artificial Aeration
SOURCE: Author, Tetra Tech Keywords

Mattingly, G.E. 1977.
EXPERIMENTAL STUDY OF WIND EFFECTS ON REAERATION.
J. Hydraul. Div., Amer. Soc. Civil Eng. 103:311-323

Wind plays a significant role in the reaeration process in lakes and streams. The calculated reaeration coefficient can jump more than one order of magnitude due to the effect of the wind. Overall, this study points out the importance of including wind measurement data when evaluating reaeration results.

DESCRIPTORS: Aeration, Wind, Wind Effects, Modeling
IDENTIFIERS: Reaeration
SOURCE: Tetra Tech

McClintock, N. 1976.
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON ZOOPLANKTON OF TWO OKLAHOMA RESERVOIRS.
M.S. Thesis, Okla. State Univ. 43 pp.

Zooplankton were collected from five depths of the central pool of Ham's Lake from April to August and from seven depths of the central pool of Arbuckle Lake from May to August, 1975. Composition, density, and diversity were observed for variation in distribution with time and depth. Effects of artificial destratification on the zooplankton assemblage were also observed.

Twenty-five and twenty-four taxa were collected from Ham's and Arbuckle Lakes, respectively. Species composition and density were similar to other area reservoirs, while diversity values (d) were consistently lower.

No correlation was observed between depth and number of species or depth and diversity. There was a tendency for density to decrease with depth. Densities were lowest in April and August in Ham's Lake and in August in Arbuckle Lake. No April sample was taken in Arbuckle Lake. In both lakes, density was highest in May.

Ham's Lake was artificially destratified by the pumping, while Arbuckle Lake was not destratified during the study. Although some temporal variation in species numbers and densities possibly reflected limited oxygen concentrations, the changes could not be directly related to physicochemical conditions of the lakes. Variations are probably due in part to seasonal population dynamics of the zooplankton. No correlation was observed between diversity and time.

DESCRIPTORS: Zooplankton, Artificial Destratification, Ham's Lake, Arbuckle Lake, Reservoirs
IDENTIFIERS: Destratification, Reservoirs
SOURCE: Author, Tetra Tech Keywords

McClintock, N., and J. Wilhm. 1977.
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON ZOOPLANKTON OF TWO OKLAHOMA RESERVOIRS.
Hydrobiologia 54:233-239.

Species composition and diversity of zooplankton were observed in two lakes undergoing destratification attempts. Twenty-five and twenty-four taxa were collected from Ham's and Arbuckle Lake, respectively. Species composition and density were similar to other area reservoirs, while diversity values (d) were consistently lower. No correlation was observed between depth and number of species or depth and diversity. Density tended to decrease with depth. Densities were lowest in April and August in Ham's Lake and in August in Arbuckle Lake. In both lakes, density was highest in May. Ham's Lake was artificially destratified by the pumping, while Arbuckle Lake was not destratified during the study. Although some temporal variation in species numbers and densities possibly reflected limited oxygen concentrations, the changes could not be directly related to physicochemical conditions of the lakes. Variations are probably due in part to seasonal population dynamics of the zooplankton. No correlation was observed between diversity and time.

DESCRIPTORS: Destratification, Reservoir, Species Composition, Density, Diversity, Zooplankton
IDENTIFIERS: Destratification, Axial-Flow Pump
SOURCE: Author, Tetra Tech Keywords

McCullough, J.R. 1974.
AERATION REVITALIZES RESERVOIR.
Water and Sewage Works 121:84-85.

Prompton Lake Reservoir was created in 1961 after construction of a flood-control dam on a mountain stream in northeastern Pennsylvania. A diffused-air mixing system, which was installed and operated in the deepest part of the reservoir during 1973, controlled algal blooms in the main basin and restored the recreational utility of the lake. Because a submarine ridge about 4,000 ft upstream of the dam effectively divided the reservoir into two pools, algal blooms continued in the upper reaches during aeration.

DESCRIPTORS: Destratification, Algal Bloom, Reservoir
IDENTIFIERS: Aeration, Reservoir
SOURCE: Tetra Tech

McLaughlin, D.K., and M.R. Givens. 1978.
A HYDRAULIC MODEL STUDY OF PROPELLER-TYPE LAKE DESTRATIFICATION PUMPS.
Technical Completion Report Oct 77-Sept 78. Oklahoma State Univ., Stillwater. 74 pp.

A hydraulic model study was performed of the local destratification phenomenon using a Garton-type propeller prototype and model experiments. Geometrically similar models of a Garton pump were constructed in varying sizes. Experiments were conducted to model the near flowfield of the propeller in the vicinity of a typical dam and release structure. The local destratification

experiments involved pumping a jet of surface water down into the heavier bottom water. With the pump located directly over the release inlet structure, the jet from the pump outflow can enhance the quality of water from the release. Successful modeling of the near flowfield of the propeller was achieved. The fundamental modeling parameter is the overall Richardson number. Important initial conditions are pump size ratios and thermocline location. A direct correlation between the nondimensional penetration depth of the jet and the dilution factor of the release samples was established. The smallest propeller was more effective at improving the quality of water from the release using the same power consumption as the other propellers.
DESCRIPTORS: Hydraulic Models, Propeller Pumps, Aeration, Lakes, Water Pollution, Model Tests, Hydrodynamics, Flow Rate, Thermoclines, Size Determination, Pumping, Depth, Prototypes, Performance Evaluation
IDENTIFIERS: Destratification, Richardson Number
SOURCE: Dialog

Monkmeyer, P.L., J.A. Hoopes, and J.C. Ho. 1972.
DESTRATIFICATION OF LAKES BY SELECTIVE WITHDRAWAL METHODS.
Technical Completion Report, Monitor OWRR-A-046-WIS(1), Water Resources Center, University of Wisconsin, Madison, Wisconsin. 25 pp.

In the pilot study, mathematical models are developed to describe two-dimensional planar and three-dimensional axisymmetric withdrawal of a viscous, non-diffusive density-stratified fluid from the bottom of a reservoir. The differential equations which describe the flow and include inertial effects are solved using the well-known Karman integral technique. Analytical solutions of the two-dimensional planar model show that the growth of the withdrawal layer is proportional to the one-fourth power of the distance from the sink. This prediction agrees closely with laboratory experiments; the axisymmetric model predicts growth of the withdrawal layer proportional to the one-fourth power of the logarithm of the radial distance from the sink. Although no laboratory verification is available at this time, an experimental study of the axisymmetric model is under way.
DESCRIPTORS: Lakes, Water Quality, Reservoirs, Pumping, Mathematical Models, Axisymmetric Flow, Bottom Water, Mixing
IDENTIFIERS: Destratification
SOURCE: Dialog

Neilson, B.J. 1974.
REAERATION DYNAMICS OF RESERVOIR DESTRATIFICATION.
J. Amer. Water Works Assoc. 66:617-620.

Use of the method of reservoir destratification with air-injection systems by United States water suppliers as a means of alleviating the taste and odor problems that accompany low dissolved-oxygen levels is discussed. The article discloses a laboratory measurement of the liquid film coefficients for the various modes of aeration.

DESCRIPTORS: Water Treatment, Aeration, Reservoirs, Thermal Stratification
IDENTIFIERS: Reaeration Dynamics, Destratification
SOURCE: Dialog

New Hampshire Water Supply and Pollution Control Commission. 1979.
EFFECTS OF DESTRATIFICATION UPON TEMPERATURE AND OTHER HABITAT REQUIREMENTS OF SALMONOID FISHES 1970-1976.
Staff Report No. 100, New Hampshire Water Supply and Pollution Control Commission, Concord, N.H. 183 pp.

The objective of this investigation was to demonstrate the feasibility of using total mixing as an alternative technique for the control of algal blooms in lakes managed for salmonid sport fishes, without jeopardizing the survival of the fish, in this case, the managed trout population. An aeration system was installed in Hot Hole Pond, a eutrophic 32-acre pond which is managed as a marginal trout fishery since the pond is plagued by an anaerobic hypolimnion during the normal summer stratification. Mixing, by introduction of compressed air at the greatest depth of the pond, 43 feet, was accomplished from 10 September to 14 October 1975 and from 4 May through 23 August 1976.

Results of this study are discussed on a parameter-by-parameter basis, and all raw data collected from 1970 through 1976 are included as an appendix to this final report. Total aeration maintained adequate oxygen concentrations in the bottom waters, with a concomitant elimination of the cold hypolimnetic waters as the entire water mass approached or occasionally exceeded potentially lethal temperature levels. However, no fish kills or distressed fish were reported or observed.

Although algal blooms have not been reported previously at Hot Hole Pond, a nuisance bloom of the blue-green algae, Anabaena spp. and Coelosphaerium spp., developed late in the mixing period of 1976 and continued into the post-mixing period. If the coincident algal bloom is a provable consequence of the mixing, then the use of this technique, for improving dissolved oxygen conditions, or any other water quality management purposes, should be selected with due regard for the prospects of associated objectionable effects, particularly the increase in phytoplankton populations.

DESCRIPTORS: Mixing, Aeration, Hypolimnion, Eutrophication, Summer Stratification, Fishes, Temperature
IDENTIFIERS: Destratification, Artificial Aeration
SOURCE: Author, Tetra Tech Keywords

Nicholas, W.R., and R.J. Ruane. 1975.
INVESTIGATION OF OXYGEN INJECTION USING SMALL-BUBBLE DIFFUSERS AT FORT PATRICK HENRY DAM.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Hydraulics Division, Gatlinburg, Tennessee, October 28-30, 1975. 19 pp.

Various aeration methods were investigated to determine the most advantageous technique for use at Fort Patrick Henry Dam. The

oxygen injection method was chosen for use upstream of the turbine intakes. The diffuser for this system will be selected on the basis of transfer efficiency, an evaluation of operation and maintenance problems, and economics.

It was found that the spacing between diffusers affects significantly the transfer efficiency of the large-pore diffuser in experimental studies. The effect of spacing on the transfer efficiency of the smaller-pore diffuser is now being evaluated.

DESCRIPTORS: Diffusers, Aeration, Air Injection, Oxygenation
IDENTIFIERS: Aeration Methods, Oxygen Injection
SOURCE: Tetra Tech

Nicholls, K.H., W. Kennedy, and C. Hammett. 1980.
A FISH-KILL IN HEART LAKE, ONTARIO, ASSOCIATED WITH THE COLLAPSE OF A MASSIVE POPULATION OF CERATIUM HIRUNDINELLA (DINOPHYCEAE).
Freshwater Biology. In Press.

A massive population of the common dinoflagellate Ceratium hirundinella developed in Heart Lake, Ontario, Canada during the summer of 1976 and its sudden collapse and subsequent decomposition depleted dissolved oxygen and resulted in a fish-kill in the lake. The lake was being artificially mixed at the time by supplying compressed air to the bottom waters and the limnological events contributing to the development of the Ceratium population and its collapse appear to be closely related to the artificial destratification process. Artificial destratification during 1976 precluded the development of blue-green algae. The process also led to an increase in the density of herbivorous zooplankters which controlled the development of smaller planktonic algae. Ceratium flourished in Heart Lake because there was little competition for nutrients from other algae and because Ceratium cells are too large to be grazed by the zooplankton. The maximum size of the Ceratium population (53 $mm^3 l^{-1}$) is apparently the highest biomass reported in the literature and its collapse may have been related to a depletion of inorganic nitrogen. There is apparently no previously published record of a Ceratium-induced fish-kill in a freshwater lake.

DESCRIPTORS: Mixing, Artificial Destratification, Fish Kill, Limnology
IDENTIFIERS: Destratification, Artificial Mixing
SOURCE: Author, Tetra Tech Keywords

Overholtz, W.J., A.W. Fast, R.A. Tubb, and R. Miller. 1977.
HYPOLIMNION OXYGENATION AND ITS EFFECTS ON THE DEPTH DISTRIBUTION OF RAINBOW TROUT (SALMO GAIRDNERI) AND GIZZARD SHAD (DOROSOMA CEPEDIANUM).
Trans. Am. Fish. Soc. 106:371-375.

The hypolimnion of a quarry pond at Ottoville, Ohio, was artificially oxygenated by using a side-stream pump. Summer concentrations of dissolved oxygen were increased from almost 0 to 8 mg/liter in 1973 and were held at or above 7 mg/liter (range 7.0-21.5) in 1974; thermal stratification was maintained in both years. In previous years, when the pond was not artificially

oxygenated or aerated by other means, rainbow trout (Salmo gairdneri) did not survive the summer because of high water temperature and oxygen depletion. One thousand rainbow trout were stocked after oxygenation in August 1973 and 800 stocked in May 1974. Anglers creeled several hundred fish each summer and gill net catch per effort remained constant during the study periods indicating that survival was probably high. Gill netting in February 1974 confirmed that trout were still present from the previous summer stocking. Trout were largely confined to the hypolimnion during thermal stratification, and were usually near its upper boundary. The fish apparently suffered no ill effects from the oxygen concentrations of 21 mg/liter in 1974. Gizzard shad (Dorosoma cepedianum) remained in the epilimnion during both summers.
DESCRIPTORS: Hypolimnion, Oxygenation, Aeration, Fish, Thermal Stratification
IDENTIFIERS: Hypolimnetic Oxygenation
SOURCE: Author, Tetra Tech Keywords

Pastorok, R.A., T.C. Ginn, and M.W. Lorenzen. 1980. REVIEW OF AERATION/CIRCULATION FOR LAKE MANAGEMENT. pp. 124-133. In: Restoration of Lakes and Inland Waters, EPA 440/5-81-010, U. S. Environmental Protection Agency, Washington, D. C.

Artificial circulation and hypolimnetic aeration are management techniques for oxygenating eutrophic lakes subject to water quality problems, algal blooms, and fishkills. Whole lake mixing may reduce regeneration of nutrients from profundal sediments, while often controlling blooms of blue-green algae. Models predict that overall algal biomass will decrease in deeper lakes when light limitation is induced by mixing. If destratification elevates epilimnetic CO_2 levels and causes a sufficient drop in pH, dominance in the algal community will likely shift from a nuisance blue-green species to a mixed assemblage of green algae. This more edible resource combined with an expansion of habitat leads to abundant zooplankton and, with provisioning of a hypolimnetic refuge, invasion of large-bodied daphnids. Habitat expansion and shifts in community structure of benthic macroinvertebrates potentially elevates the abundance of fish food organisms. Although short-term increases in fish growth and yield have been attributed to improvements of food and habitat resources, documentation of long term changes is lacking. In southern regions, artificial circulation provides benefits for warmwater fishes only.
DESCRIPTORS: Aeration, Circulation, Reservoir Mixing, Nutrients, Phytoplankton Species, Zooplankton, Benthos, Fish, Review
IDENTIFIERS: Destratification Effects
SOURCE: Tetra Tech

Pastorok, R.A., T.C. Ginn, and M.W. Lorenzen. 1980.
EVALUATION OF AERATION/CIRCULATION AS A LAKE RESTORATION TECHNIQUE.
EPA 600/3-81-014, U.S. Environmental Protection Agency, Corvallis,Oregon.

Artificial circulation is achieved by injecting diffused air into lower waters, by mechanical pumping of water from one depth stratum to another, or by inducing turbulence at the surface using large axial-flow pumps. In contrast, hypolimnetic aeration by air or oxygen injection affects primarily bottom waters; in some instances, low dissolved oxygen concentrations persist in the metalimnion. In general, both restoration methods lower the concentrations of reduced compounds (e.g., Fe, Mn, NH_4, H_2S) in lake waters, providing benefits for water supply systems. Although aeration/circulation sometimes aggravates oxygen deficits,adverse impacts can be minimized by proper design of techniques and manipulation of biological responses.

Whole lake mixing may control blooms of blue-green algae. Models predict that overall algal biomass will decrease in deeper lakes when light limitation is induced by mixing. If destratification elevates epilimnetic CO_2 levels and drops pH, dominance in the algal community will likely shift from a nuisance blue-green species to a mixed assemblage of green algae. This more edible resource combined with an expansion of habitat leads to more abundant zooplankton. In most cases, treatment enhances the abundance and species richness of benthic macroinvertebrates in the profundal zone. Although short-term increases in fish growth and yield have been attributed to improvements of food and habitat resources, documentation of long-term changes is lacking.

Hypolimnetic aeration maintains the natural thermal structure of the lake while oxygenating bottom waters. Thus, this technique is preferred for management of water supply systems and cold-water fisheries. While hypolimnetic treatment usually lowers phosphate concentrations in bottom waters, the long-term effects on internal nutrient loading and phytoplankton response is unknown. Hypolimnetic aeration or oxygenation appears to allow habitat expansion in zooplankton and benthic macroinvertebrates as well as fishes.

DESCRIPTORS: Aeration, Circulation, Hypolimnion, Mixing, Reservoirs, Water Quality, Phytoplankton, Zooplankton, Benthic Macroinvertebrates, Fish, Review
IDENTIFIERS: Destratification, Hypolimnetic Aeration, Diffused Air, Mechanical Pumps
SOURCE: Tetra Tech

Peterson, J.O., S.M. Born, and R.C. Dunst. 1974.
LAKE REHABILITATION TECHNIQUES AND EXPERIENCES.
Water Resour. Bull. 10:1228-1245.

It is stressed that degradation of many lakes is the result of aging processes which have been accelerated by the activities of man. Where it is too late to prevent sedimentation and eutrophication problems, lake rehabilitation and protection comprise a resource management option warranting serious consideration. A

Wisconsin Lake Renewal Demonstration Project has been evaluating several rehabilitation schemes for the past five years. A selected summary of Project lake rehabilitation activities, including nutrient inactivation, dilution, aeration, and several types of aquatic plant management, is presented.
DESCRIPTORS: Lakes, Improvement, Water Resources
IDENTIFIERS: Lake Restoration, Aeration
SOURCE: Dialog, Tetra Tech Identifiers

Proctor, J.A. 1973.
REAERATION TESTS AT TABLE ROCK DAM.
Arkansas Professional Engineer. June (1973):2-11.

Turbine releases from Table Rock Dam are deficient in dissolved oxygen from late summer to December. The trout fishery in downstream areas is seriously endangered. To correct this problem aeration tests were conducted, including direct air injection into turbines and air diffusion into the lake immediately upstream of the power intakes. Monitoring of dissolved oxygen and temperature was carried out in the reservoir and in downstream areas.

At medium generation rates, air aspirated through the turbine vent increases dissolved oxygen to levels acceptable for a downstream trout fishery. When power load cannot be spread over all turbines or generation rates are high, air injection at an upstream point in the penstock can achieve desired oxygen concentrations. Air diffusion tests were not as effectiv- as penstock aeration; positioning of air diffusers closer to the penstock yielded better results.
DESCRIPTORS: Reservoir, Aeration, Turbine, Diffusers, Downstream, Fishery
IDENTIFIERS: Aeration, Power Intakes
SOURCE: Tetra Tech

Quigley, J.T., and W.C. Boyle. 1976.
MODELING OF VENTED HYDRO TURBINE REAERATION.
J. Water Pollut. Control Fed. 48:357-366.

A general model is proposed to describe performance of turbine vents in relation to power losses. Tests of the model were conducted using an experimental turbine. Initial dissolved oxygen increases of up to 4.1 mg/l were possible, with induced air flows exhibiting a "voided" or two-phase flow regime in the upper draft tube. Operation resulted in a significant reduction in peak power attainable.
DESCRIPTORS: Reaeration, Turbine, Reservoir Discharge, Air Vent, Draft Tube, Diffuser
IDENTIFIERS: Turbine, Aeration
SOURCE: Tetra Tech

Quigley, J.T., J.R Villemonte, and W.C. Boyle. 1975.
VENTED HYDROTURBINE AERATION AND POWER FOREGONE.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975. 34 pp.

In order to develop a generalized model for the prediction of aeration and power performance of hydroturbine installations when vented for purposes of stream reaeration, an available eight-inch diameter, straight draft tube Kaplan hydroturbine was modified to permit accurate power and pressure measurement while introducing air below the runner. The turbine was operated in a pumpturbine-reservoir system with water flows of 1000 to 1600 gpm and air flows of 12 to 70 cfm air flow. In general, a sufficient vacuum was maintained in the turbine draft tube to induce necessary air flows. The test program was designed to determine hydroturbine power foregone during periods of vented operation. Specifically, two-level factorial design was used to assess the effects of runner speed, water rate, and air-water ratio on several diffuser designs.

The most significant effect of vented draft tube operation was determined to be a reduction in the peak power attainable rather than an operating loss. From the data taken, vented draft tube operation might be thought of as a throttled condition to be compensated for in the gating or guide vane arrangement.

Air was distributed well below the runner. Despite these design precautions, voids did form in the water column at the higher air-water ratios and conditions of greatest stress in the liquid phase. The level of mixing and conditions affecting the formation of interfacial area between the gas and liquid phases were strongly influenced by these voids and oxygen transfer rates improved markedly.

DESCRIPTORS: Aeration, Hydroturbine, Turbine, Reaeration, Mixing
IDENTIFIERS: Aeration, Water Treatment
SOURCE: Author, Tetra Tech Keywords

Quintero, J.E., and J.E. Garton. 1973.
A LOW ENERGY LAKE DESTRATIFIER.
Trans. Am. Soc. Agr. Eng. 16:973-978.

An axial-flow propeller pump was designed, built, and tested for application in lake destratification. Equations were developed to describe the flow and power versus propeller rpm, diffuser diameter and diffuser length. Large discharge volumes were possible with low energy input. Rotation velocity of the propeller shaft was the main factor affecting flow and power. Pumping efficiency was low, being less than 46 percent. About 10 hp would probably be needed to power a 40-ft pump with a capacity of 10^6 gal/min. The pump should be a practical method for moving surface water toward the reservoir bottom to achieve destratification or raise oxygen content locally.

DESCRIPTORS: Axial-Flow Pump, Mixing, Reservoir, Water Quality, Pump Efficiency, Power, Energy Input
IDENTIFIERS: Destratification, Propeller Pump

SOURCE: Tetra Tech

Raney, D.C. 1975.
TURBINE AIR ASPIRATION FOR DISSOLVED OXYGEN SUPPLEMENTATION.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975. 32 pp.

An experimental program in turbine aspiration has been conducted to develop techniques for improving the dissolved oxygen level of hydroelectric discharges. The program involved water tunnel modeling of aspiration systems in addition to prototype installations on existing hydroelectric facilities. Design data for aspiration systems are presented.

DESCRIPTORS: Aeration, Turbine Aspiration, Discharge, Water Tunnel Modeling

IDENTIFIERS: Aspiration Systems, Modeling

SOURCE: Dialog

Raynes, J.J. 1975.
CASE STUDY - ALLATOONA RESERVOIR.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinberg, Tennessee. 14 pp.

Artificial circulation and mixing techniques can be used to break up stratification in an impoundment and effectively manage water quality problems. In Allatoona Reservoir, an air diffusion system was installed about ten feet above the lake bottom. The mixing system decreased surface temperatures, increased bottom temperatures, and hastened fall turnover. The dissolved oxygen content of impounded water and of downstream releases was generally enhanced. Aeration treatment appeared to decrease iron and manganese levels at depths below 45 ft. Short term effects on plankton and benthos seemed minimal, being restricted to an area surrounding the diffusers. Initial investment for the system was about $85,000 to $100,000, and annual operation costs are about $40,000.

DESCRIPTORS: Reservoir, Circulation, Mixing, Water Quality, Plankton, Benthos

IDENTIFIERS: Artificial Circulation, Air Diffusion, Destratification

SOURCE: Tetra Tech

Reaeration Research Program Management Team. 1975.
REAERATION AND CONTROL OF DISSOLVED GASES - A PROGRESS REPORT.
Bur. Reclam. Rep. REC-ERC-75-1, Div. Gen. Res. Bureau of Reclamation, Denver, CO, 22 p.

The research program, Reaeration and Control of Dissolved Gases, has emphasized destratification of reservoirs, biological effects of reaeration and destratification, dissolved gas levels at energy dissipator structures, conception of new methods and devices for reaeration, and corrosion by molecular oxygen. Destratification

testing has occurred at Flaming Gorge Reservoir and Lake of the Arbuckles and is being planned for Lake Casitas. Research on biological effects at Lake of the Arbuckles is receiving support and a comprehensive state-of-the-art report has been issued. A dissolved gas level prediction method has been developed from data collection from a wide variety of types of energy dissipators. Laboratory testing on the corrosive effects of the use of molecular oxygen is underway.
DESCRIPTORS: Aeration, Dissolved Oxygen, Reaeration, Dissolved Gases, Energy Dissipators, Supersaturation, Corrosion Tests, Reservoirs, Streams
IDENTIFIERS: Destratification (Thermal), Flaming Gorge Reservoir, UT, Lake of the Arbuckles, OK, Lake Casitas, CA
SOURCE: Author

Reider, W.G. 1977.
WIND POWERED ARTIFICIAL AERATION OF NORTHERN PRAIRIE LAKES.
Res. Proj. Tech. Completion Rept., N. Dakota Water Resour. Res. Inst., Fargo, N.D. 121 pp.

Most northern prairie lakes suffer from recurring oxygen depletion, and, although artificial aeration seems to help, operating costs are becoming high because of increasing energy costs. An alternate source of compressed air for operating the aeration systems is wind-powered compressors. A detailed assessment of the feasibility of this approach in North Dakota settings was completed. A large number of wind-turbine and compressor combinations was investigated. Methodology for matching commercial compressors to various wind turbines and predicting output rates based on wind spectrum inputs was developed and verified. Optimum gear-up ratios exist for maximum air output rates. A small experimental wind-powered compressed-air system was built and operated successfully at a non-lake site. Economic analyses were completed. Findings indicate that the use of wind to power small compressors (less than about 15 SCFM) for artificial aeration in North Dakota is technically and economically feasible within certain constraints. Recommendations include proceeding into prototype system installations at lake sites in North Dakota
DESCRIPTORS: Oxygen, North Dakota
IDENTIFIERS: Wind Turbines, Destratification
SOURCE: Dialog

Rogers, H.H., J.J. Raynes, E.H. Posey, Jr., and W.E. Ruland. 1973.
LAKE DESTRATIFICATION BY UNDERWATER AIR DIFFUSION.
pp. 572-577. In: W.C. Ackerman (ed.). Man-made lakes: Their problems and environmental effects. Geophys. Monogr. Ser. V. 17, Amer. Geophys. Union, Washington, D.C.

An air diffuser system was installed in Allatoona Lake to destratify and increase the oxygen content of the impounded water. Water quality was improved while the system was in operation. The dissolved oxygen levels in the lake were maintained above 4.0 mg/l

level while the aeration equipment was in continuous operation, except for a few days in early August before the fall turnover began.
DESCRIPTORS: Aeration, Circulation, Mixing, Reservoir, Water Quality
IDENTIFIERS: Destratification, Air Diffusion
SOURCE: Tetra Tech

Ruane, R.J., and S. Vigander. 1973.
OXYGENATION OF TURBINE DISCHARGES FROM FORT PATRICK HENRY DAM.
pp. 291-310. In: R.E. Speece (ed.). Applications of commercial oxygen to water and wastewater systems. University of Texas, Austin, Texas.

The Tennessee Valley Authority is investigating the use of oxygen injection through fine-pore diffusers for increasing dissolved oxygen concentrations in the turbine discharges from Fort Patrick Henry Dam. Oxygen injection is being considered either immediately upstream from the turbine intakes, so that the oxygenated water is drawn directly into the turbines, or immediately downstream from the "boil" area in the tailrace.

Research is being conducted in two phases: (1) selection of a diffuser for injecting the oxygen, and (2) selection of the best location for injecting the oxygen. In Phase I, various commercial diffusers are being evaluated for possible plugging problems and for oxygen absorption efficiency. Field and laboratory tests indicate that diffuser-plugging apparently is not a significant problem and that oxygen absorption efficiency approaching 100 percent can be achieved in a 42-foot height of bubble rise with several commercially available diffusers. In Phase II, a large-scale diffuser system will be evaluated at Fort Patrick Henry Dam during the summer and fall of 1973.

A full-scale system will be installed at the dam if results of this research show this method of reaeration to be technically and economically feasible.
DESCRIPTORS: Oxygenation, Turbine Discharges, Tailrace, Diffusers
IDENTIFIERS: Oxygenation, Power Turbines
SOURCE: Author, Tetra Tech Keywords

Ryabov, A.K., B.I. Nabivanets, Zh.M. Aryamova, Ye.M. Palamarchuk, and I.S. Kozlova. 1972.
EFFECT OF ARTIFICIAL AERATION ON WATER QUALITY.
Hydrobiol. J. 8:49-52.

This article examines the effect of artificial aeration on oxygen saturation, pH, carbonate balance, and rate and nature of mineralization of organic matter in natural waters. The preliminary findings of this study show that artificial aeration alters the qualitative and quantitative composition of phytoplankton and sharply intensifies the decomposition and mineralization of nitrogenous organic compounds.
DESCRIPTORS: Aeration, Water Quality, Nitrogen Compounds, Mineralization

IDENTIFIERS: Artificial Aeration
SOURCE: Tetra Tech

Ryabov, A.K., T.Ya. Smikun, L.V. Podgayevskaya, and Zh.M. Aryamova. 1978.
THE EFFECTS OF ARTIFICIAL AERATION ON SELF-PURIFICATION OF WATER IN SETTLING PONDS AT A SUGAR REFINERY.
Hydrobiol. J. 14:21-27.

The dynamics of the chemical composition of water and of the changes in the mycoflora under the influence of aeration by bubbling air are described.

The use of artificial aeration in the ponds of the Bobrovitsa Sugar Refinery caused an increase in the rate of mineralization of nitrogenous organic compounds, as a result of which the organoleptic properties of the water were improved. Artificial aeration depressed the development of blue-green algae in the spring-summer season.

DESCRIPTORS: Artificial Circulation, Diffused Air, Water Quality, Settling Ponds, Phytoplankton
IDENTIFIERS: Mixing, Aeration
SOURCE: Author, Tetra Tech Keywords

Schierholz, P.M. et al. 1976.
WIND POWERED AERATION FOR REMOTE LOCATIONS.
Final Report, March 15, 1975 - August 31, 1976. Colorado State University, Energy Research and Development Administration, Fort Collins, Colorado. 152 pp.

Wind-powered aerators were installed and operated at three fish winterkill lakes and at a sewage lagoon. A wind-powered aerator is a system that converts the energy in the wind directly into compressed air which can be used in an aeration process. No auxiliary energy storage is required in that the lake acts as a storage device for the oxygen. None of the lakes where wind-powered aerators were installed experienced fish winterkill during the 1975-1976 winter. Wind-powered aeration shows promise for increasing sewage lagoon capacity only under severe weather conditions. The most desirable wind-powered aerator would be an American Wind Turbine driving a rotary blower mounted on a single pole tower. The winds are of sufficient strength and frequency for wind-powered aeration in northeastern Colorado and southeastern Wyoming, between the Front Range and the Continental Divide.

DESCRIPTORS: Lakes, Wind Turbines, Aeration, Colorado, Monitoring, Performance Testing, Uses, Wyoming
IDENTIFIERS: ERDA/170601, Aerators
SOURCE: Dialog

Schoumacher, R. 1974.
LAKE DESTRATIFICATION INVESTIGATIONS JOB I-1: LITERATURE REVIEW ON DESTRATIFICATION, JULY 1, 1972 TO JUNE 30, 1974.

Final Report, D-J Project F-19-R, West Virginia Department of Natural Resources.

Lake aeration provides the water manager and fishery manager with a valuable tool for environmental alteration. Destratification is easily accomplished in small and moderate-sized impoundments using compressed air, and hypolimnion aeration has also been applied successfully as a management tool. Destratification results in the orthograde distribution of most physical and chemical water quality parameters, whereas hypolimnion aeration improves water quality while retaining stratification and the cold water resources of the hypolimnion. The quantitative response of phytoplankton to aeration is not so well documented but several authors report a shift in taxon dominance favoring greens over blue-greens. Zooplankton have generally extended their distribution into deeper water following aeration. Destratification of eutrophic lakes results in large increases in benthos, especially chironomids, in deeper water. Fishery benefits from aeration include an increase in the quantity of water inhabitable by fish, increases in the supply of benthos available for food, and prevention of winter kills.

DESCRIPTORS: Destratification, Aeration, Water Quality Management, Hypolimnion Aeration, Phytoplankton, Zooplankton, Benthos, Fish

IDENTIFIERS: Destratification, Review

SOURCE: Author, Tetra Tech Keywords

Shapiro, J. 1973.
BLUE-GREEN ALGAE: WHY THEY BECOME DOMINANT.
Science 197:382-383.

The injection of carbon dioxide and the addition of nitrogen and phosphorus to a lake population dominated by blue-green algae results in a rapid shift to dominance by green algae. The basis for the change and its implications are discussed.

DESCRIPTORS: Mixing, Aeration, Blue-green Algae, Green Algae, Experimental Enclosures

IDENTIFIERS: Destratification, Diffused Air

SOURCE: Author, Tetra Tech Keywords

Shapiro, J., V. LaMarra, and M. Lynch. 1975.
BIOMANIPULATION: AN ECOSYSTEM APPROACH TO LAKE RESTORATION.
pp. 85-96. In: Proc. Sympos. on Water Quality Management through Biological Control, P.L. Brezonik and J.L. Fox (eds.). Univ. Florida and U.S. Environ. Prot. Agency. Gainesville, FL.

This paper presents the results of experiments directed at controlling eutrophication by manipulations of the biological community. For example, fish are shown to be an important source of zooplankton mortality and nutrient regeneration; addition of zooplanktivores to experimental enclosures results in significant increases in photosynthesis, chlorophyll and a decrease in phosphate. Artificial circulation of Lake Calhoun distributed fish and zooplankton throughout a greater lake volume than before treatment, reducing predator-prey encounter rate and allowing a large increase of _Daphnia_ populations.

Mixing of the water column and additions of nutrients in experimental enclosures produces a shift in dominance among phytoplankton species, from blue-green algae to green algae. Nutrient addition fails to cause the shift by itself, instead increasing the abundance of blue-green species. It is postulated that a lowering of pH mediated by additions of hypolimnetic CO_2 into the upper layer causes the shift in algal dominance. Although the exact mechanism is uncertain, alterations of relative competitive advantage or activation of cyanophages (blue-green viruses) could play a role in the algal shift. Artificial destratification of lakes mixes hypolimnetic CO_2 and nutrients into the upper waters; after an effective mix, pH of the former epilimnion decreases and a shift from blue-green algae to green algae may result.
DESCRIPTORS: Mixing, Artificial Circulation, Biomanipulation, Fish, Zooplankton, Blue-green Algae, Green Algae, Experimental
IDENTIFIERS: Destratification, Diffused Air, Enclosures
SOURCE: Tetra Tech

Shapiro, J., G. Zoto, and V. Lamarra. 1977.
EXPERIMENTAL STUDIES ON CHANGING ALGAL POPULATIONS FROM BLUE-GREENS TO GREENS.
Limnological Research Center, Minnesota University, Minneapolis. 30 pp.

This research involves shifting of algal populations for possible lake restoration work. The site was Lake Emily, a small, shallow lake north of St. Paul, Minnesota. The research supports the notion that as phosphate becomes available, those algae that are able to outcompete others for it will become predominant. The work may have great value in lake restoration. Continuing studies indicate that the same factors operating to cause the shifts are responsible for shifts brought about by artificial circulation.
DESCRIPTORS: Algae, Circulation, Water Pollution Control, Lake Emily, Cyanophyta, Chlorophyta, Food Chains, Inorganic Phosphates, pH, Carbon Dioxide, Nitrogen, Field Tests, Aeration, Minnesota
IDENTIFIERS: Aeration, Lake Restoration
SOURCE: Dialog, Tetra Tech Identifiers

Sikorowa, A. 1978.
CHANGES OF THE DISTRIBUTION AND NUMBER OF THE BOTTOM FAUNA AS AN EFFECT OF ARTIFICIAL LAKE AERATION.
Verh. Internat. Verein. Limnol. 20:1000-1003.

Effects of deep aeration on macrobenthos was observed in the eutrophic Lake Starodworskie. The lake is small, with an area of 7 ha and maximal depth 23 m, situated in the northeastern part of Poland. Simultaneously physico-chemical studies were undertaken, as were observations of phytoplankton, primary production, zooplankton and bacterial microflora.

Aeration started in March 1972 and ended in September 1973. The air was introduced constantly, to the lake bottom, using a compressor with the efficiency of 16 m^3 of air/h (Lossow et al. 1975). Aeration period was preceded by complex studies, carried

out in an annual cycle, while the effects of aeration were observed in a 2-year cycle (April 1971-March 1972 and April 1972-February 1974). Samples of bottom fauna were collected once a month, along a transversal axis of the lake, at the depths of 1.5-2.0 m, 4-5 m, 10, 15 and 23 m.

Over-eutrophication of Lake Starodworskie, worsened by an unfavourable bradymictic system, was observed in natural conditions. During summer 10% of the bottom area had anaeorobic conditions, and in extreme cases in winter oxygen disappeared in total water volume (Olszewski 1959; Paschalski 1963; Lossow and Drozd 1976).

Aeration totally changed existing thermal and oxygen situation. As a result of upward movement of warmer waters in winter, ice cover disappeared. Complete homothermy and homooxygenia were formed. In March water temperature reached 3.7° C, and at the end of summer bottom temperatures amounted to 10° C compared to 4° C before the experiment. Oxygen content in the bottom layer increased considerably, while its content in the surface layer (very high before the experiment) decreased. Processes of decomposition and nitrification of organic matter accelerated and in autumn precipitation to bottom sediments was observed.

DESCRIPTORS: Artificial Aeration, Lake Eutrophication, Macrobenthos, Destratification
IDENTIFIERS: Aeration, Artificial Destratification
SOURCE: Author, Tetra Tech Keywords

Sirenko, L.A., N.V. Avil'tseva, and V.M. Chernousova. 1972.
EFFECT OF ARTIFICIAL AERATION OF POND WATER ON THE ALGAL FLORA.
Hydrobiol. J. 8:52-58.

Aeration of ponds by bubbling results in destratification and uniform oxygen concentration throughout the pond, thereby eliminating stagnant zones with a low oxygen content in the bottom layers. Aeration also greatly changes the nature of the algal communities. The blue-green algae responsible for water blooms are eliminated, the development of other algal groups, chiefly the Protococcaceae, is promoted. Water quality is also improved.

DESCRIPTORS: Aeration, Water Quality, Algal Communities, Pond
IDENTIFIERS: Artificial Aeration, Destratification
SOURCE: Author, Tetra Tech Keywords

Smith, D.R. 1980.
SYNOPSIS OF WES EWQOS INVESTIGATIONS TO IMPROVE WATER QUALITY BY GAS TRANSFER TECHNIQUES BOTH IN THE RESERVOIR AND IN THE RELEASE.
Proc. Seminar on Water Quality Evaluation, Committee on Water Quality, U.S. Army Corps of Engineers, Engineering Division. Tampa, Florida, 22-24 January, 1980.

This paper reviews recent work on gas transfer techniques conducted by the Hydraulics Laboratory of the Waterways Experiment Station. Hypolimnetic oxygenation increased dissolved oxygen concentrations in the near field (100 ft from injector) and in the far field (one mile from the injector); however, nitrogen

concentrations increased significantly only in the near field due to denitrification of resuspended sediments. A line source diffusion system was more effective at enhancing dissolved oxygen than a rectangular array. A study of pneumatic destratification in eleven reservoirs showed the technique was effective in elevating oxygen content, but it caused nitrogen supersaturation in lower waters relative to the surface. Nitrogen supersaturation up to 135% may cause little problem in the reservoir but releases should be degassed. Hydraulic model studies of gas transfer in outlet works indicate oxygen uptake increases linearly with unit discharge and linearly for the range of Froude numbers investigated. A spillway model with a flip lip showed 37% increase in oxygen transfer without excessive nitrogen supersaturation.
DESCRIPTORS: Gas Transfer Techniques, Reservoir, Oxygen Level, Nitrogen Supersaturation, Hydraulic Models
IDENTIFIERS: Aeration, Oxygenation, destratification
SOURCE: Tetra Tech

Smith, H.A., Jr. 1974.
SPILLWAY REDESIGN ABATES GAS SUPERSATURATION IN COLUMBIA RIVER.
U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon. 4 pp.

Polluted streams are uninhabitable for fish because the water has too little dissolved air. Ironically, the Columbia and Snake Rivers in the Northwest sometimes kill fish because of too much dissolved air, so-called nitrogen supersaturation. The main culprits are dam spillways that churn huge volumes of air into the river, threatening the $50 million/yr salmon industry there. The most promising solution the Corps of Engineers has evolved so far is the spillway deflector, a concrete sill placed near the base of a spillway to divert flow horizontally.
DESCRIPTORS: Spillway, Gas Supersaturation, Columbia River, Nitrogen, Flow
IDENTIFIERS: Deflectors, Supersaturation
SOURCE: Author, Tetra Tech Keywords

Smith, S.A., D.R. Knauer, and T.L. Wirth. 1975.
AERATION AS A LAKE MANAGEMENT TECHNIQUE.
Wisconsin Dept. Natur. Resour., Tech. Bull. No. 87. 39 pp.

The objective of this project was to demonstrate the feasibility of hypolimnetic aeration as a useful technique for lake restoration. In order to successfully evaluate hypolimnetic aeration, aerators were installed in two eutrophic lakes in central Wisconsin. The major component of the hypolimnetic aerator consisted of a 40-ft long, 18-inch-diameter polyethylene tube with an internal longitudinal plate dividing the tube in half and twisted to form a helix. Compressed air or a combination of compressed air and liquid oxygen were supplied to the base of the unit and water was air lifted up the tube to enter a 4-ft by 4-ft by 8-ft bubble separation box at the surface of the lake, where the air bubbles

were vented to the atmosphere. The bubble-free oxygenated water was returned to the hypolimnion via two 18-inch-diameter flexible return tubes. An evaluation of the unit was completed in a eutrophic, clear, hard water lake (Mirror) in 1972 and 1973 and in a dystrophic soft water lake (Larson) in 1973. The initial studies indicated that all of the oxygen transfer from the compressor occurred in the bottom half of the unit, with further transfer occurring in the surface separation box as the water momentarily came in contact with the atmosphere.

Under operating conditions at Mirror Lake with an air supply of 16 cfm and a water flow moving through the aerator at 4.2 cfs, the dissolved oxygen transfer was 20 percent. A combination of compressed air at 16 cfm and liquid oxygen at 5.5 cfm was supplied to the aerator giving a water flow of 5.3 cfs and an oxygen transfer efficiency of 23 percent. The oxygen transfer efficiency at Larson Lake with compressed air only was between 12 and 14 percent.

Both Mirror and Larson lakes had anoxic hypolimnia during the summer months. Attempts at satisfying the very high oxygen demands in Mirror Lake (maximum biological oxygen demand in the bottom water was 39 mg/l before aeration) were unsuccessful during limited aeration in 1972 and extended operation in 1973. However, the operation of the aerator in Larson Lake proved successful. Dissolved oxygen concentrations in the hypolimnion increased from 0.0 to 7.0 mg/l. At present, establishment of a cold water fishery appears possible in Larson Lake and current research has indicated a trout population can be maintained in the hypolimnion.

DESCRIPTORS: Lake Management, Aeration, Hypolimnion, Eutrophication
IDENTIFIERS: Hypolimnetic Aeration, Artificial Aeration
SOURCE: Author, Tetra Tech Keywords

Sobey, R.J, and S.B. Savage. 1974.
JET-FORCED CIRCULATIONS IN WATER-SUPPLY RESERVOIRS.
J. Hydraul. Div., Amer. Soc. Civil Eng. 100:1809-1828.

A detailed understanding of the large-scale current motions in reservoirs is a fundamental prerequisite to their successful water quality management. A theoretical and experimental study of the throughflow-forced circulating flow within a reservoir gyre of simplified geometry is presented. Dimensional analysis and flow visualization are used to define the essential features of the flow. An integral-type mathematical model, containing no free parameters, is then presented and subsequently verified against laboratory experiments. This mathematical model is extrapolated to a real-reservoir parameter range to define a jet-forced circulation diagram. This diagram, which should be useful in the preliminary design of water-supply reservoirs, nondimensionally relates the jet-forced circulation to: (1) The reservoir aspect ratio and the boundary roughness; (2) The jet Reynolds number; and (3) The jet geometry having been shown to be relatively unimportant.

DESCRIPTORS: Flow of Water, Jets, Reservoirs, Mathematical Models
IDENTIFIERS: Water Quality
SOURCE: Dialog

Speece, R.E. 1975a.
OXYGEN RESTORATION TO WATERS RELEASED FROM CLARK HILL RESERVOIR.
Final Report. Prepared for U.S. Army Corps of Engineers, Savannah, Georgia.
59 pp.

During late summer and early autumn, a problem of low dissolved oxygen levels occurs in the water released from Clark Hill Reservoir. Protection of a trout habitat in the downstream reach below this impoundment mandates that water quality standards of 6 mg/l be maintained. This report reviews and evaluates potential aeration methods including: (1) surface aeration, (2) air or oxygen injection into the impoundment, (3) spillway aeration, (4) air or oxygen injection into the penstock, (5) side stream oxygenation, (6) multilevel penstock intake, (7) submerged weirs, and (8) localized destratification. The best choice for aeration of Clark Hill Reservoir discharges would be injection of commercial oxygen produced at a location close to the dam.

DESCRIPTORS: Oxygenation, Aeration, Diffused Air, Fishery, Water Quality, Reservoir Discharge, Circulation
IDENTIFIERS: Artificial Aeration, Oxygenation
SOURCE: Tetra Tech

Speece, R.E. 1975b.
OXYGENATION OF CLARK HILL RESERVOIR DISCHARGES.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975. 38 pp.

By late August or early September, hypolimnetic waters in Clark Hill Reservoir are nearly devoid of dissolved oxygen, causing downstream oxygen levels to drop below the water quality standard of 6 mg/l. This paper reviews possible methods of supplementing dissolved oxygen in Clark Hill discharges during the critical period. The aeration methods reviewed include: (1) surface aeration by standard wastewater treatment equipment, (2) air or oxygen injection into the impoundment, (3) spillway aeration, (4) penstock air or oxygen injection, (5) sidestream oxygenation, (6) multilevel penstock intake (7) submerged weirs, and (8) localized destratification. On-site oxygen production is favored over oxygen transport to site. The recommended method is injection of oxygen into the hypolimnion forming an unconfined bubble plume about 1 mi upstream of the dam. Continuous oxygen diffusion from an array of nine racks at a rate of 12 tons rack^{-1} day^{-1} would form the basis for an initial demonstration study.

DESCRIPTORS: Oxygenation, Diffused Air, Aeration, Fishery, Water Quality, Reservoir Discharge
IDENTIFIERS: Artificial Aeration, Oxygenation
SOURCE: Tetra Tech

Speece, R.E., F. Rayyan, and G. Murfee. 1973a.
ALTERNATIVE CONSIDERATIONS IN THE OXYGENATION OF RESERVOIR DISCHARGES AND RIVERS.
pp. 342-361. In: R.E. Speece (ed.). Applications of commercial oxygen to water and wastewater systems. University of Texas, Austin, Texas.

Two alternative methods for supplemental oxygenation of reservoir discharges and rivers were considered - deep oxygen bubble injection and Downflow Bubble Contact Aeration. The first method can accomplish hypolimnion oxygenation in reservoirs having 10 to 15 meters of bubble rise height below the metalimnion. Efficient oxygen absorption is achieved, stratification of the reservoir is maintained, and oxygen distribution within the hypolimnion is facilitated by the bubble plume. Initial bubble diameters of 1 to 2 mm exhibit comparable absorption characteristics to 0.2-mm bubbles on the basis of percent absorbed in a given rise height. Therefore, economics favor the bubble diffusers producing the larger bubble sizes because they are cheaper.

The Downflow Bubble Contact Aerator can efficiently dissolve high purity oxygen in shallow water applications such as in river oxygenation. The DO increment resulting from each pass through the system is proportional to the hydrostatic head. At shallow submergences, DO increment is more controlled by inlet DO than at deeper submergences.

The particular features of a given situation will determine which oxygen supplementation system is most suitable.

DESCRIPTORS: Oxygenation, Reservoir Discharges, Rivers, Hypolimnion, Bubble Characteristics, Gas Transfer
IDENTIFIERS: Oxygen Injection, Downflow Bubble Contact Aeration
SOURCE: Author, Tetra Tech Keywords

Speece, R.E., F. Rayyan, and G. Murfee. 1973b.
HYPOLIMNION AERATION WITH COMMERCIAL OXYGEN. VOLUME I. DYNAMICS OF BUBBLE PLUME.
U.S. EPA, Technology Series Report No. EPA-600/2-73-025a. 189 pp.

This study deals with a proposed scheme for restoration and maintenance of dissolved oxygen in the hypolimnion of stratified impoundments without disturbing the stratification. The characteristics of a bubble-water plume, as used in hypolimnion aeration, were studied. The major factor introduced in the study of these characteristics was the effect of mass transfer. A mathematical model was developed for this case and compared with a mathematical model which neglects the effect of mass transfer. The model calculates the diameter of the bubble, the diameter of the plume, the velocity of plume rise, the water flow rate, and the momentum and energy flux for the rising plume at any level above the diffuser. It also calculates the amount of oxygen absorbed at any level and the increase of the dissolved oxygen concentration in the plume for any oxygen flow rate.

DESCRIPTORS: Reservoirs, Stratification, Aeration, Water Quality, Oxygenation, Bubbles, Plumes, Dissolved Gases, Oxygen, Mass Transfer, Fluid Dynamics, Mathematical Models, Computer Programs

IDENTIFIERS: Hypolimnion
SOURCE: Dialog

Speece, R.E. F. Rayya nd G. Murfee. 1973c.
HYPOLIMNION AERATION WITH COMMERCIAL OXYGEN. VOLUME II. BUBBLE PLUME GAS TRANSFER.
U.S. EPA, Technology Series Report No. EPA-660/2-73-025b. 157 pp.

The study deals with a proposed scheme for restoration and maintenance of dissolved oxygen in the hypolimnion of stratified impoundments without disturbing the stratification. A mathematical model was developed for predicting the gas transfer characteristics of a bubble plume within an impoundment. Particular attention was given to evaluation of the gas transfer coefficient as a function of bubble size. Tables were compiled from the calibrated model. These tables predict the oxygen absorption characteristics which can be expected for various field situations.
DESCRIPTORS: Water Quality, Aeration, Reservoirs, Stratification, Dissolved Gases, Oxygen, Bubbles, Plumes, Mathematical Models, Mass Transfer, Absorption
IDENTIFIERS: Hypolimnion
SOURCE: Dialog

Speece, R.E., R.H. Siddiqi, R. Auburt, and E. DiMond. 1976.
RESERVOIR DISCHARGE OXYGENATION DEMONSTRATION OF CLARK HILL LAKE.
Final Report. Prepared for U.S. Army Corps of Engineers, Savannah District.

This study investigated using different-sized diffusers to produce a better dissolved oxygen content in the water released from Clark Hill Lake. Half of the diffuser system was replaced with diffusers which were smaller pore size. This allowed the system to generate smaller bubbles (about 2-mm diameter as compared with 4-5 mm diameter with the original diffusers). The location of the diffusers proved important in securing the maximum equipment performance. It was found that oxygen transfer efficiency increases when sufficient contact time is allowed for the rising air bubbles before they are discharged through the turbines. Injection of 51 tons/day oxygen at 120 ft away from the intake allowed about 120 sec contact time with a discharge of 2940 cfs; this produced a discharge DO of 7.6 mg/l and 93 percent oxygen absorption efficiency.
DESCRIPTORS: Oxygen Injection, Water Quality, Dissolved Oxygen, Diffuser Design
IDENTIFIERS: Oxygenation
SOURCE: Tetra Tech

Steel, J.A. 1972.
THE APPLICATION OF FUNDAMENTAL LIMNOLOGICAL RESEARCH IN WATER SUPPLY SYSTEM DESIGN AND MANAGEMENT.
Symp. Zool. Soc. Lond. 29:41-67.

Consideration is given to a potable water treatment system which includes an impoundment stage, particular emphasis being

accorded to this unit. If such impoundments thermally stratify, then difficulties may be occasioned for water supply by de-oxygenation of the hypolimnion, and the phytoplankton population of the epilimnion. Of primary importance is the loss of available volume caused by the hypolimnetic anaerobism. It is briefly indicated that this may be solved by preventing thermal stratification and supplying sufficient oxygen to the mud surface so as to maintain an oxidized microzone. In the basins considered, the energy requirement to effect this is about 40 g-cm/cm^2 day, and the oxygen demand per unit mud surface is assessed as 4.0 g O_2/m^2 day. Systems are now available which can, economically, supply energy at many times this rate. These energetic capabilities can alter the impounded water's characteristics so as to affect the biota. A "limiting" circulation depth of "Spring" diatoms is, in these waters, suggested to be almost 30 m. Some adverse effects of turbulence are indicated. Grazing by herbivorous zooplankton is suggested to be an important factor in reducing summer phytoplankton crops. The level of this grazing load, taken as twice the daphnid daily assimilation rate, is approximately 0.05-0.10 g C/m^2 day during winter, and can become 1.0-2.0 g C/m^2 day during summer. It is suggested that husbandry of such zooplankton would be desirable, and some means to effect this are discussed. It is possible that, with regard to phytoplankton, one of these means might allow a degree of "negative feedback" to be incorporated in the system. Such design and/or management would allow some system optimization, in which unit outputs are more closely suited to succeeding units.
DESCRIPTORS: Water Treatment, Hypolimnion, Zooplankton, Phytoplankton, Impoundment, Limnology
IDENTIFIERS: Aeration, Destratification
SOURCE: Author, Tetra Tech Keywords

Steichen, J.M., J.E. Garton, and C.E. Rice. 1974.
THE EFFECT OF LAKE DESTRATIFICATION ON WATER QUALITY PARAMETERS.
Ann. Meeting of Amer. Soc. of Agric. Engineers.

A small stratified lake was destratified using a low power, high volume axial flow pump. The effect of destratification on several water quality parameters was observed.
DESCRIPTORS: Axial-Flow Pump, Destratification, Water Quality
IDENTIFIERS: Artificial Aeration, Mixing
SOURCE: Author, Tetra Tech Keywords

Steichen, J.M., J.E. Garton, and C.E. Rice. 1979.
THE EFFECT OF LAKE DESTRATIFICATION ON WATER QUALITY.
J. Amer. Water Works Assoc. 71:219-225.

The axial-flow-type pump built by Quintero was modified to incorporate more propeller blades, vary propeller blade pitch and add a rigid diffuser. Operation of the pump at Ham's Lake accomplished thermal destratification within two weeks, although a longer period of pumping was required for destratification of dissolved oxygen. Blue-green algae dominated before pumping, whereas greens prospered after treatment.

Pumping caused a decrease in epilimnetic pH and an increase in hypolimnetic pH almost immediately. After mixing, there was a rapid decline in five-day biochemical oxygen demand. The destratification efficiency was 6.0 percent without the diffuser and 4.6 percent with the diffuser. The propeller resulted in as much as 49 percent more flow at the same power compared with the Quintero pump.
DESCRIPTORS: Mixing, Axial-Flow Pump, Destratification Efficiency, Water Quality, Phytoplankton
IDENTIFIERS: Destratification, Propeller Pump
SOURCE: Tetra Tech

Strecker, R.G., J.M. Steichen, J.F. Garton, and C.E. Rice. 1977.
IMPROVING LAKE WATER QUALITY BY DESTRATIFICATION.
Trans. Am. Soc. Agric. Eng. 20:713-720.

A low-energy (746 W), high-volume (1.6 m^3/sec) axial flow, propeller (1.8 m diameter) pump was designed and operated on a small (40 ha surface area, 9.5 m maximum depth, and 115 ha-m volume) stratified lake. The objectives were: (a) to design and construct a prototype, low-energy, axial-flow propeller pump for use as a destratification device; (b) to evaluate the performance of the pump when moving water under a small head; and (c) to determine the effect of the pump's operation on the water quality parameters of a stratified lake.

Four days of pumping were required to warm the bottom water to the surface water temperature with a resultant destratification efficiency of 3.3% for the period. Dissolved oxygen was maintained above 2.0 mg/l in the lower waters of the reservoir and above 5.0 mg/l in the surface waters. The overall water quality in the reservoir was improved.

The fan laws provided an effective means of predicting the performance in water from the available data in air. The angle of divergence for the discharge cone was between 21 and 28 degrees and considerable amounts of water were entrained at the periphery of the discharge cone.
DESCRIPTORS: Mixing, Axial-Flow Pump, Propeller, Water Quality, Destratification Efficiency
IDENTIFIERS: Destratification, Garton Pump
SOURCE: Author, Tetra Tech Keywords

Strus, R. 1976.
EFFECTS OF ARTIFICIAL DESTRATIFICATION ON ZOOPLANKTON OF HEART LAKE, ONTARIO.
Water Resources Branch, Ontario Ministry of the Environment, Ontario, Canada. 18 pp.

Heart Lake, a eutrophic body of water in Southern Ontario, was artificially destratified by aeration from June to September, 1975 and May to September, 1976 (the treatment year). Early summer crustacean zooplankton populations exhibited an increase as aeration began probably resulting from oxygenation of previously anoxic bottom waters and subsequent downward expansion of zooplankton

populations. No significant differences in mean zooplankton density (in no/m^3) between the control year (1968-69) and the treatment year could be found.

The zooplankton of Heart Lake indicated characteristica eutrophic conditions, with no clear change visible between contr... and treatment year indicator species. A large, new zooplankter, Daphnia pulex, appeared in 1976, replacing the smaller D. rosea, while the cold water-adapted Cyclops bicuspidatus thomasi was replaced by the warm water Mesocyclops edax and Tropocyclops prasinus mexicanus during the six year interval between the treatment and control years.

Aeration of Heart Lake bottom waters (previously anaerobic during summertime) has opened up a relatively predation-free habitat in this zone, resulting in the increased frequency of larger species of zooplankton (notably D. pulex). Consequently, an improved summertime food resource existed for planktivorous fish in the upper waters, as evidenced by examination of rainbow trout stomach contents, daphnid size decrease and daphnid helmet production. Additionally, increased algal filtering rates during 1976 by the greater numbers of larger sized zooplankton may have created some ecological selection for an algal species unaffected by zooplankton grazing, Ceratium hirundinella.

DESCRIPTORS: Artificial Destratification, Aeration, Oxygenation, Zooplankton, Eutrophication

IDENTIFIERS: Destratification, Aquatic Management

SOURCE: Author, Tetra Tech Keywords

Summerfelt, R.C., and G. Gebhart. 1976.
FISH GROWTH RESPONSE TO MECHANICAL MIXING OF LAKE ARBUCKLE, OKLAHOMA.
Tech. Completion Rep. OWRT A-048-OKLA, Oklahoma Water Resour. Res. Inst., Stillwater. 104 p.

Fish were sampled from 1973-75 to determine the effect of mechanical mixing of Lake Arbuckle, Oklahoma, on the growth rate and depth distribution of gizzard shad, white crappie, freshwater drum, black bullhead and channel catfish. The vertical depth distribution, annual growth rate, instantaneous growth rate, seasonal growth rate and condition factors were determined for the above species. The vertical depth distributions of all species were compressed into the upper water layers by an anoxic hypolimnion during summer stratification and the distributions deepened substantially after fall overturn. No positive conclusions about annual growth rates could be resolved, but it appeared that growth was generally larger in 1974 when the lake was partially mixed than in previous nonmixed years. Seasonal growth rates indicated that generally the major portion of the population growth occurred during the destratified overwinter period rather than the stratified summer period. Condition factors often decreased during the stratified summer interval and increased during the destratified period indicating better fish conditions when the lake was destratified.

DESCRIPTORS: Fresh Water Fishes, Aeration, Growth, Lake Arbuckle, Mixing, Stratification, Depth, Seasonal Variations, Catfishes, Carp,

Dissolved Gases, Oxygen, Temperature, Abundance, Correlation Techniques, Tables (Data), Oklahoma
IDENTIFIERS: Destratification, Hypolimnion, Dissolved Oxygen, *Cyprinus carpio*, *Pomoxis annularis*, *Ictalurus punctatus*, *Ictalurus melas*, *Aplodinotus grunniens*, *Dorosoma cepedianum*
SOURCE: Dialog

Taggart, C.T., and D.J. McQueen. In Press.
HYPOLIMNETIC AERATION OF A SMALL EUTROPHIC KETTLE LAKE: PHYSICAL AND CHEMICAL CHANGES.
York University, Department of Biology, Toronto, Ontario. 32 pp. + figures.

Tory Lake, Ontario (1.23 ha, 10 m max. depth) received hypolimnetic aeration for two successive summers (May - October, 1978, 1979). The small portable aerator did not disturb stratification and raised oxygen concentrations (average 2.42 mg/L 1978, and 1.47 mg/L 1979) in the hypolimnion. During the summers of both years total Kjeldahl-N slowly increased in the hypolimnion. NO_3-N concentrations remained low. In the fall NH_3 was nitrified to NO_3 which slowly decreased during the winter. Total hypolimnetic phosphorus increased during the summer but the total mass of P was lower in 1979 than in 1978. Soluble Mn decreased as a result of aeration and may have been removed in phosphate complexes. In both summers the metalimnion was virtually anoxic by July, and remained so until fall turnover. H_2S increased in the metalimnion but was almost absent in the hypolimnion. We conclude that hypolimnetic aeration is a useful lake restoration technique. However, a method must be found to eliminate anoxic metalimnia which are potential barriers to lake biota.

DESCRIPTORS: Hypolimnion, Aeration, Lake Restoration
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Author, Tetra Tech Keywords

Toetz, D.W. 1977a.
BIOLOGICAL AND WATER QUALITY EFFECTS OF WHOLE LAKE MIXING.
Final Tech. Rep. A-068-OKLA. Oklahoma Water Resour. Res. Inst. 78 pp.

An axial flow pump designed by James Garton offers a cost-effective solution to water quality problems. The goal of this research was to describe water quality and biological effects of the Garton pump. The pump advanced fall turnover by one month and reduced vertical thermal differences during the summer in Arbuckle Lake (950 ha). There was no effect of mixing on the vertical distribution of reducing compounds, algal biomass or transparency. Ham's Lake (40 ha) was destratified each summer during 1973-1976. Algal biomass and fish growth were unchanged. The effects of lake mixing on the biota were investigated using isolated columns of water. Community production (P) and respiration (R) declined in isolated columns of lake water and mixing reduced both still further, but the ratio P/R was unchanged.

DESCRIPTORS: Axial Flow Pumps, Aeration, Lakes, Reservoirs, Water Pollution Control, Algae, Fishes, Primary Biological Productivity,

Mixing, Stratification, Plankton, Respiration, Arbuckle Lake, Biomass, Ham's Lake
IDENTIFIERS: Destratification
SOURCE: Dialog

Toetz, D. 1977b.
EFFECTS OF LAKE MIXING WITH AN AXIAL FLOW PUMP ON WATER CHEMISTRY AND PHYTOPLANKTON.
Hydrobiologia 55:129-138.

This paper describes the effect of total lake mixing with an axial flow (Garton) pump on the limnology and phytoplankton of two Oklahoma lakes.

The Garton pump destratified Ham's Lake (40 ha) in 3 days. Except for one small isolated basin, Ham's Lake remained completely destratified for the rest of the summer. Algal biomass declined, numbers of species of green algae increased, but numbers of species of blue-green algae did not decrease as expected. After destratification, pH remained high (>8), carbonate alkalinity was observed and reactive phosphate was undetectable.

An axial flow pump increased the heat content of Arbuckle Lake (951 ha) and caused the lake to destratify about one month earlier than usual. Increasing the heat content of the lake did not affect the concentration of most water quality parameters or the biomass of algae.

DESCRIPTORS: Artificial Destratification, Lake Mixing, Water Quality, Water Chemistry, Phytoplankton, Biomass, Blue-Green Algae, Green Algae, Reservoir, Oklahoma
IDENTIFIERS: Mixing, Destratification, Water Chemistry
SOURCE: Author, Tetra Tech Identifiers

Toetz, D.W. 1979a.
BIOLOGICAL AND WATER QUALITY EFFECTS OF ARTIFICIAL MIXING OF ARBUCKLE LAKE, OKLAHOMA, DURING 1977.
Hydrobiologia 63:255-262.

This paper describes the effects of total lake mixing with 16 axial flow (Garton) pumps on the water quality, algal biomass and community metabolism of Arbuckle Lake, Oklahoma.

Pumping began on July 1, 1977, and subsequently lowered the thermocline throughout the lake. The concentration of dissolved oxygen rose in formerly anoxic strata. Water quality in the former hypolimnion improved. Concentration of ammonia and BOD_5 decreased, and concentrations of manganese remained unchanged in 1977 compared to the control year (1976). But, concentrations of sulfide in the hypolimnion were higher in 1977 than in 1976. Algal biomass as chlorophyll a was about the same in 1977 as in 1978. The depth of the Secchi disc was also the same. An algal bloom did not occur. Pumping decreased the ratio gross production: community respiration as measured by a free water method, suggesting that lakes which are artificially mixed will have lower net primary productivities than lakes which are not artificially mixed.

DESCRIPTORS: Artificial Destratification, Lake Mixing, Water Quality, Water Chemistry, Algal Biomass, Chlorophyll a, Community Metabolism, Reservoir, Oklahoma
IDENTIFIERS: Destratification, Mixing, Water Quality
SOURCE: Author, Tetra Tech Identifiers

Toetz, D.W. 1979b.
EFFECTS OF WHOLE LAKE MIXING ON ALGAE, FISH, AND WATER QUALITY.
Technical Completion Report A-078-OKLA, Oklahoma Water Resources Research Institute, Oklahoma State University. 56 pp.

This report describes the effects of artificial mixing of two Oklahoma lakes with a downflow (Garton) pump on water quality, algal biomass and community metabolism. Artificial pumping in Arbuckle Lake (951 ha), advanced the autumnal turnover, but never completely destratified the lake. Ammonia and BOD_5 decreased in the epilimnion, while dissolved oxygen (DO) increased and sulfide ($S^{=}$) declined in the hypolimnion. Near-bottom concentrations of Mn^{++} increased. Pumping did not change significantly the depth of the Secchi disc or algal biomass. Community metabolism data failed to confirm that artificial lake mixing changes the ecosystem from autotrophic to heterotrophic.

The Garton pump seldom produced completely isothermal conditions or isochemical concentrations of DO in Ham's Lake (41 ha) and no measurable change in water quality, but pumping decreased water clarity and increased algal biomass.

DESCRIPTORS: Reservoir, Artificial Destratification, Water Quality, Algal Biomass, Community Metabolism, Oklahoma
IDENTIFIERS: Destratification, Artificial Mixing, Hypolimnion, Epilimnion
SOURCE: Author, Tetra Tech Identifiers

Toetz, D., J. Wilhm, and R. Summerfelt. 1972.
BIOLOGICAL EFFECTS OF ARTIFICIAL DESTRATIFICATION AND AERATION IN LAKES AND RESERVOIRS - ANALYSIS AND BIBLIOGRAPHY.
Oklahoma Cooperative Fishery Unit Rept. No. REC-ERC-72-33. 128 pp.

The state of the art of research concerning the biological effects of reaeration and destratification is described, with emphasis on lakes and reservoirs. Research needs are discussed, based on this review. Useful descriptions of methods and devices for reaeration and destratification and a comprehensive annotated bibliography of 337 references are included.

DESCRIPTORS: Lakes, Aeration, Limnology, Aeration, Reservoirs, Mixing, Water Quality, Lakes, Bibliographies, Stratification, Thermal Gradients, Water Pollution, Aerators, Dissolved Gases, Oxygen, Aquatic Microbiology, Metals, Trace Elements, Nutrients, Algae, Zooplankton, Invertebrates, Fresh Water Fishes, Turbidity, Ecology, Benthos
IDENTIFIERS: Destratification, Water Pollution Control
SOURCE: Dialog

Tolland, H.G. 1977.
DESTRATIFICATION/AERATION IN RESERVOIRS.
Tech. Rep. No. TR50. Water Research Centre, Medmenham, UK. 37 pp.

This review of the literature emphasizes performance criteria, operation costs, and effects of destratification and hypolimnetic aeration. Short-term oxygenation capacity and destratification efficiency may not be valid as design criteria because of time dependence during actual operation of a device.

Continuous operation of destratification systems to prevent stratification is recommended rather than installation after water quality problems have arisen. Since most oxygenation occurs by atmospheric transfer at the reservoir surface, system improvements are more likely to be made by increasing momentum transfer and inducing greater mixing. Air injection methods, air and mechanical pumps, and jetted inlets are used for destratification. Mechanical pumps on pontoons are generally inefficient and difficult to maintain. Optimum jet angle and location of jets are primary design considerations. Air-lift pumps involving vertical stacks do not offer any advantage over diffusers, yet the former require more capital expense. Jets are particularly expensive to install. For aeration systems, the initial cost per reservoir volume and the operating cost per volume decline as the volume of the reservoir increases. Design details are given for a number of previous destratification and hypolimnetic aeration experiments.

DESCRIPTORS: Review, Destratification, Aeration, Hypolimnion, Pumps, Water Jets, Oxygenation Capacity, Efficiency, Costs, Design
IDENTIFIERS: Destratification, Aeration, Design
SOURCE: Tetra Tech

Tolland, H.G. 1978.
THEORETICAL ASPECTS OF THE OPTIMIZATION OF JETTED-INLET DESIGN.
Report LR 828, Water Research Centre, Medmenham Laboratory, U.K.

The use of Steel's approximate trajectory equation enables jet design to be considered in a reasonably quantitative manner. Several general design points emerge: (1) Two or more jets should be provided to give a choice between jet angles; (2) Inclined jets should be constructed in a hollow. The design should ensure that entrainment commences at about the level of the reservoir bottom; (3) Simple control rules can be derived to guide the reservoir operator in his choice of jets; (4) Jet angles should be chosen by utilizing the known jet dynamic properties. This is especially true if it is only possible to provide one jet angle.

DESCRIPTORS: Jetted-Inlet, Flow, Water Jet Design, Theory, Entrainment
IDENTIFIERS: Water Jet, Destratification
SOURCE: Author, Tetra Tech Keywords

Torrest, R.S., and J. Wen. 1976.
MIXING AND CIRCULATION OF LAKES AND RESERVOIRS WITH AIR PLUMES.

Completion Report RR-13, New Hampshire University, Durham. 135 pp.

Aeration of lakes and reservoirs to control eutrophication and improve water quality is widespread. However, there are few guidelines to aid in design of the aeration treatment. Here relevant fluid mechanics literature is first summarized to show that the nature of the flow of water entrained by air bubbles rising from manifolds and point sources may be well described. Experimental studies of the resulting surface flows supplement and extend previous work. Surface velocity decay is described and, for manifold aeration, the circulation cell size is shown to be about four times the water depth on each side of the manifold. Detailed measurements of velocity profiles are presented for a wide range of aeration rates in channels to 1-1/2 feet wide, 4 feet high and 12 feet long. The influence of aerator design and depth is illustrated, as is the variation of circulation efficiency with aeration rate. Similar results for 'point source' aeration to 9 SCFM are described. Circulation due to water injection from a manifold (i.e., jet injected) is compared with that due to aeration. Measurements of the time variation of dissolved oxygen within the primary circulaion are well described by a simple mathematical model with the single parameter, the time constant, a function of aeration rate. These results should aid in the overall design of aeration treatments since the characteristics of aeration induced circulation and the resulting dissolved oxygen variation can be estimated for systems of interest.

DESCRIPTORS: Aeration, Lakes, Reservoirs, Water Pollution Control, Fluid Mechanics, Nutrients, Sediments, Oxygen, Dissolved Gases, Mathematical Models, Stratification, Experimental Design, Heat Exchange, Circulation, Plumes, Velocity, Efficiency

IDENTIFIERS: Eutrophication, Currents, Water

SOURCE: Dialog

Turner, H.J., R.E. Towne, and T.P. Frost. 1972.
CONTROL OF ALGAE BY MIXING.
J. N. Engl. Water Works Assoc. 86:267-275.

Water quality of Kezar Lake, New Hampshire, declined due to blooms of the copper sulphate resistant algae, Aphanizomenon. During several summers the lake was destratified by injection of diffused air. In 1969 tests, algal cell counts dropped from 10^6 cells/ml near the surface before mixing to 3 x 10^4 cells/ml after mixing. As a result of treatment, dissolved oxygen rose to 5.7 mg/l in the previously anoxic hypolimnion. Transparency of the lake improved greatly. The algal community shifted from blue-greens to less objectionable green algae. Similar results were obtained in tests during subsequent years.

DESCRIPTORS: Mixing, Diffused Air, Water Quality, Phytoplankton, Transparency

IDENTIFIERS: Destratification, Aeration

SOURCE: Tetra Tech

U.S. Army Corps of Engineers. 1972.
TABLE ROCK AERATION TESTS.
Final Report. Little Rock District, Little Rock, Arkansas.

This report presents data on dissolved oxygen and temperature in Table Rock Lake and a downstream lake, Lake Taneycomo. Aeration tests were performed to determine the best method for raising the dissolved oxygen level downstream of Table Rock Lake. Results of the aeration tests indicated that dissolved oxygen concentrations can be increased by using diffusers or direct injection of compressed air into the penstock or draft tube.

Injection was more effective because of the inability of the diffusers to aerate the entire withdrawal zone. Turbine vent aeration moderates the need for artificial aeration, suggesting that direct injection into the vent may be the most economical mode of supplemental aeration. The aeration tests caused no measurable change in water quality of Table Rock Lake or Lake Taneycomo.

DESCRIPTORS: Aeration, Turbine Vent, Penstock, Reservoir, Water Quality, Dissolved Oxygen.

IDENTIFIERS: Air Diffusers, Air Injection, Reservoir Discharge

SOURCE: Tetra Tech

U.S. Army Corps of Engineers. 1973.
ALLATOONA LAKE, DESTRATIFICATION EQUIPMENT TEST REPORT.
U.S. Army Engineer District, Savannah, Georgia. 64 pp.

This report investigates the effectiveness of destratification equipment used to improve the water quality of Allatoona Lake. A diffuser air pump which operated in 1968-1969 discharged about 2000 feet upstream from the dam. This system provided a thermal destratification efficiency of 0.3 and 0.7 percent in the lake during 1968 and 1969, respectively. The diffused air pump elevated dissolved oxygen concentrations in the lake possibly as far as 4 mi upstream of the dam. Aeration may have produced an increase in concentration of carbon dioxide, Kjeldahl nitrogen, and ammonia, and reductions in total hardness, conductivity, turbidity, total iron, total and dissolved manganese, and nitrate plus nitrite nitrogen. Some parameters remained unchanged by treatment, e.g. sulfide, alkalinity, total and dissolved phosphates, and pH. Treatment appeared to have little short-term effect on plankton and benthos within the reservoir, although studies of downstream benthos indicated a possible increase in taxonomic diversity of the community. Equipment costs are also evaluated.

DESCRIPTORS: Diffuser, Aeration, Reservoir, Circulation, Mixing, Water Quality, Downstream Benthos

IDENTIFIERS: Artificial Aeration, Destratification

SOURCE: Tetra Tech

Vigander, S. 1975.
SELECTION OF OXYGEN DIFFUSERS.
Symp. on Reaeration Research, Amer. Soc. Civil Eng., Gatlinburg, Tennessee, October 28-30, 1975. 6 pp.

Of several methods considered by TVA for the reaeration of hydraulic turbine releases, one consists of generating a multitude of small oxygen gas bubbles near the bottom of the head pool immediately upstream from the turbine intakes. Oxygen is transferred from the rising gas bubbles to the water that later passes through the turbines. The bubbles are generated by forcing oxygen gas through the porous surface of a diffuser.

The paper describes laboratory tests made to evaluate the oxygenation efficiencies of a commercially available diffuser materials over certain ranges of pore sizes and oxygen supply rates.
DESCRIPTORS: Reaeration, Oxygenation, Diffusers, Pore Size
IDENTIFIERS: Oxygen Diffuser, Efficency
SOURCE: Author, Tetra Tech Keywords

Vigander, S., and R.J. Ruane. 1975.
OXYGENATION SYSTEM DEVELOPMENT FOR TURBINE DISCHARGE AERATION.
Proc. 16th Congress, Int. Assoc. for Hydraul. Res., July 27-Aug. 1, 1975, Sao Paulo, Brazil. 3:346-355.

At several of TVA's multipurpose, tributary storage reservoirs with hydroelectric power turbines, the thermal lake stratification in the summer causes release of water with low concentrations of dissolved oxygen. A research program was initiated in 1971 for the development of a system to reaerate turbine releases back up to the desired dissolved oxygen concentrations. The system described uses oxygen gas injected in the form of small bubbles which rise from the bottom of the lake near the turbine intakes. The paper presents data on oxygenation efficiency as a function of oxygen flux, turbine flow, and the distance between the dam and the oxygen injection point for a pilot aeration plant of approximately the size of a 10 MW unit. Aeration efficiencies were obtained from 30 to 90%.
DESCRIPTORS: Water Treatment, Aeration, Water Pollution, Waste Heat Effects, Hydroelectrical Power Plants, Hydraulic Turbines Oxygenation, Aeration
IDENTIFIERS: Oxygenation, Aeration
SOURCE: Dialog, Tetra Tech Identifiers

Weiss, C.M., and B.W. Breedlove. 1973.
WATER QUALITY CHANGES IN AN IMPOUNDMENT AS A CONSEQUENCE OF ARTIFICIAL DESTRATIFICATION.
Rept. No. 80, N. Carolina Water Resour. Res. Inst., 236 p.

The effects of destratification on a water supply impoundment were studied over a three-year period. Prior to destratification, baseline information on physical, chemical and biological parameters was established. Destratification was accomplished by the use of the 'Air-aqua' system which creates vertical circulation in a body of water by the release of small bubbles from hoses laid on the lake bottom. In addition to a monitoring program to establish changes in physical and chemical characteristics of the water, the plankton populations, benthic organisms and periphyton accumulations were studied. Also, a creel census was taken and information on the

operation of the water treatment plant which uses University Lake as a raw water supply was analyzed.
DESCRIPTORS: University Lake, Limnology, Reservoirs, Mixing, Water Quality, Temperature, Oxygen, Dissolved Gases, pH, Color, Turbidity, Chlorophylls, Nutrients, Benthos, North Carolina, Water Supply, Phytoplankton, Algae, Diptera, Aeration, Chemical Composition, Water Treatment
IDENTIFIERS: Periphyton, Destratification, Midges, Chironomidae
SOURCE: Dialog

Whipple, W., Jr., J.V. Hunter, F.B. Trama, and T.J. Tuffey. 1975.
OXIDATION OF LAKE AND IMPOUNDMENT HYPOLIMNIA.
Water Resour. Res. Inst., Rutgers Univ. Final Rept. on Proj. No. B-050-N.J. 97 pp.
This is the completion report of research to determine the effect of oxygenation on the hypolimnia of eutrophic lakes. It was carried out at Spruce Run Reservoir in New Jersey. A new type of oxygenator was used which dissolves oxygen into the lower depths of the lake, in water masses directed horizontally in slow but turbulent currents, which do not disturb stratification. The apparatus uses liquid oxygen, and fine pore diffusers. The efficiency of the operation was less than anticipated; but sufficent oxygen was introduced to maintain trout and alewives during the summer season.
DESCRIPTORS: Oxygenation, Limnology, Water Pollution, Spruce Run Reservoir, Water Analysis, Inorganic Phosphates, Biochemical Oxygen Demand, Oxygen, Dissolved Gases, Stratification, Diffusion, Benthos, Nutrients, Fishes, New Jersey
IDENTIFIERS: Hypolimnion, Eutrophication, Dissolved Oxygen
SOURCE: Dialog

Wilhelms, S.C. 1975.
REAERATION THROUGH HYDRAULIC STRUCTURES.
U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi. 22 pp.
Dissolved gas data from physical models and prototype structures were analyzed to determine relationships of the model/prototype reaeration characteristics. Similar prototypes may exhibit similar gas-exchange characteristics. However, the model/prototype scaling laws were not evident on the existing model. Further investigation is necessary.
DESCRIPTORS: Reaeration, Hydraulic Structures, Modeling
IDENTIFIERS: Reaeration
SOURCE: Author, Tetra Tech Identifiers

Wilhm, J., and N. McClintock. 1978.
DISSOLVED OXYGEN CONCENTRATION AND DIVERSITY OF BENTHIC MACROINVERTEBRATES IN AN ARTIFICIALLY DESTRATIFIED LAKE.
Hydrobiologia 57:163-166.

Changes in species composition and diversity of benthic macroinvertebrates during summer and fall were compared in an area of a lake artificially destratified and in an arm not destratified. Numbers of species, diversity, and density were significantly correlated with the concentration of dissolved oxygen, while none of the biotic variables were correlated with temperature.
DESCRIPTORS: Destratification, Dissolved Oxygen, Diversity, Benthic Macroinvertebrates
IDENTIFIERS: Artificial Destratification
SOURCE: Author, Tetra Tech Identifiers

Wilhm, J.L., D. Barker, E. Clay, and N. McClintock. 1977.
POPULATION OF BENTHIC MACROINVERTEBRATES IN HAM'S LAKE.
Final Completion Report. Oklahoma Water Resources Research Institute, Stillwater, Oklahoma. 25 pp.

Ham's Lake, Oklahoma, was destratified during summer 1976 by pumping surface water to the bottom. Number of species, diversity, and density of benthic macroinvertebrates were significantly correlated with the concentration of dissolved oxygen, while none of the biotic variables was correlated with temperature. Percent loss on ignition and $CaCO_3$ of the sediments generally decreased with increasing sediment depth. During 1977 pumping was not applied. The variables measured will be compared with values obtained in 1978 when the lake will again be destratified. A gradual decrease in hemolymph ions (Na^+, K^+, CL^-) in Chaoborus punctipennis was observed from May through September and a return to higher concentrations in October. The lake water at the bottom contained low concentrations of these ions until August. A decrease in osmotic pressure was measured in C. punctipennis during the summer reflecting the trends in fluctuation of hemolymph ions.
DESCRIPTORS: Oxygen, Invertebrates, Water Pollution, Ham's Lake, Sampling, Dissolved Gases, Sediments, Particle Size, pH, Benthos, Larvae, Turbidity, Calcium Carbonates, Temperature, Oklahoma
IDENTIFIERS: Destratification, Species Diversity, Water Pollution Effects, Animals, Chaoborus punctipennis
SOURCE: Dialog

Wilhm, J., D. Barker, E. Cover, E. Clay, and R. Fehler. 1979.
EFFECTS OF DESTRATIFICATION ON SEDIMENT CHEMISTRY AND BENTHIC MACROINVERTEBRATES IN HAM'S LAKE.
Final Technical Completion Report A-079-OKLA, Oklahoma Water Resources Research Institute, Oklahoma State University. 36 pp.

Spatial and temporal changes in the physicochemical conditions and heavy metals of the water and sediments, and physiological conditions in Chaoborus punctipennis and Chironomus riparius were studied in Ham's Lake from 14 Apr 77 - 22 Sep 79. Oxygen-rich surface water was pumped to the bottom in the central pool in summers 1978 and 1979. Changes in the central pool were compared with an adjacent area prevented from mixing by a submerged dam of a former farm pond. Dissolved oxygen was 3-5 mg/l and temperature

6-8^{o} C greater in the mixed area than in the unmixed area. Other variations between the mixed and unmixed areas include a greater concentration of sorbed manganese in the sediments and a lower concentration of total manganese in the water at the mixed area, greater concentration of organic matter in the stratified area, and greater oxygen uptake and hemolymph Na^{+} concentration of Chaoborus in the stratified area. Particle size of the sediments was smaller at 8-m depth than at 2-m depths, while kaolinite and quartz were the dominant constituents of the sediments.
DESCRIPTORS: Hypolimnion, Artificial Destratification, Benthic Macroinvertebrates, Stratification, Eutrophic, Lake, Anoxic, Aeration, Monitoring, Sediments, Particle Size
IDENTIFIERS: Thermal Stratification, Destratification, Hypolimnion, Water Quality Data
SOURCE: Author, Tetra Tech Keywords

Wirth, T.L., D.R. Knauer, and S.A. Smith. 1974.
TOTAL AND HYPOLIMNETIC AERATION OF LAKES IN WISCONSIN.
Verh. Internat. Verein. Limnol. 19:1960-1970.

Hypolimnetic aeration and total lake mixing can increase dissolved oxygen levels in lakes, if properly designed. In lakes that do not mix thoroughly or long enough to satisfy oxygen demands, total compressed air mixing in spring and fall is an easy means of insuring satisfaction of oxygen demands and providing the maximum quantity of dissolved oxygen available so the lake may better withstand oxygen demand during summer and winter periods of stagnation. Hypolimnetic aeration without destratification is feasible during summer stratification. During the winter, density gradients are small, so that destratification of most of the water column is certain. In the hypolimnetic aerator described, water flow through the unit is greatly reduced if the air-lifted water must overcome even a small head. Enriching compressed air with pure oxygen provided more optimum water flows and oxygen transfer than using either alone. Almost all of the oxygen transfer took place in the lower half of the 12.2-m "Helixor" component of the aerator.
DESCRIPTORS: Fish, Invertebrate, Eutrophication, Season
IDENTIFIERS: Hypolimnetic Aeration
SOURCE: Dialog, Author, Tetra Tech Keywords

Yu, S.L., T.J. Tuffey, and D.S. Lee. 1977.
ATMOSPHERIC REAERATION IN A LAKE.
Completion Report, Rutgers State University, New Brunswick, N.J. 60 pp.

An investigation of reaeration and its relationship to aerodynamic and hydrodynamic variables was conducted. Mass transfer and boundary layer theories are utilized to formulate a functional relationship between the reaeration coefficient and pertinent physical parameters. Field work was carried out in Spruce Run Reservoir (located in Central N.J.) to obtain actual measurements of these parameters. Correlation analysis was then performed to yield several best-fit equations. Wind speeds were measured at three

different heights above the surface level of the water within the plastic-lined circular pools, which were the apparatus adopted for experimentation. Results show that wind speed is a limiting factor affecting reaeration in a lake. The highest correlation was with speed at the lowest height, indicating that the reaeration coefficient, K_2 is a function of surface turbulence created by wind. These equations are capable of predicting reaeration coefficients of water systems under the circumstance where the air motion is a predominant source of turbulence.
DESCRIPTORS: Aeration, Hydrodynamics, Wind Velocity, Spruce Run Reservoir, Water Pollution Abatement, Air-Water Interactions, Oxygenation, Mass Transfer, Turbulent Boundary Layer, Oxygen, Correlation Techniques, Dissolved Gases, Monitoring, New Jersey
IDENTIFIERS: Reaeration, Atmospheric Boundary Layer
SOURCE: Dialog

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Pastorok, Robert A.
Environmental aspects of artificial aeration and oxygenation of reservoirs: A review of theory, techniques, and experiences / by Robert A. Pastorok, Marc W. Lorenzen, and Thomas C. Ginn (Tetra Tech, Inc.). -- Vicksburg, Miss. : U.S. Army Engineer Waterways Experiment Station ; Springfield, Va. : available from NTIS, 1982.
192, 85 p. ; ill. ; 27 cm. -- (Technical report ; E-82-3)
Cover title.
"May 1982."
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"Monitored by Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station."
"Environmental & Water Quality Operational Studies."
Bibliography: p. 165-192.

Pastorok, Robert A.
Environmental aspects of artificial aeration : ... 1982.
(Card 2)

1. Environmental impact analysis. 2. Reservoirs--Aeration. 3. Water quality. I. Lorenzen, Marc W. II. Ginn, Thomas C. III. United States. Army. Corps of Engineers. Office of the Chief of Engineers. IV. U.S. Army Engineer Waterways Experiment Station. Environmental Laboratory. V. Environmental & Water Quality Operational Studies. VI. Title VII. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; E-82-3.
TA7.W34 no.E-82-3